Conservation Planning for Antarctic Stations

by

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Declaration of originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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Statement of Co-Authorship

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Abstract

The ice-free areas of Antarctica make up less than half a percent of the continent but are vital locations for scientific and biodiversity values: providing key habitats for the two vascular plant species, mosses, lichens, invertebrates, the majority of vertebrate breeding sites, and the most accessible locations for studying geoheritage. Human activity is also disproportionately concentrated within these ice-free areas, with the most pronounced impacts from the construction and operation of research stations. As a consequence of their locations, despite stations appearing to be small against the scale of the continent, their footprints can have profound impacts on nearby values, warranting conservation. To address this, an understanding of the term 'footprint', as it applies to stations, is first provided to aid conservation planning and standardise terminology. This is followed by an investigation of contemporary environmental accidents in Antarctica, finding that, while a substantial portion of the current footprint of stations originate from discontinued practices, the largest source of new human impacts, with a main exception of fuel spills, were from planned and permitted activities. To provide context for broad-scale conservation management, this thesis then provides the first report quantifying the footprint of station infrastructure across all Antarctica: with >390,000 m^2 of buildings, and an additional disturbance footprint of >5,200,000 m^2 just on ice-free land. The significance of this disturbance is further amplified by an analysis finding multiple physical and biological impacts occur in sites of visibly disturbed substrate across Antarctica's ice-free regions. Drawing upon the knowledge gained, this thesis concludes by providing an approach to balance this footprint against obligations to protect the environment, agreed upon under the Antarctic Treaty System, through improved, strategic, and deliberate conservation planning of station sites.

Introduction

Preface

On terrestrial Antarctica, infrastructure and logistics associated with research stations have more pronounced *in situ* environmental impacts than any other human activity. These stations have spread across the continent in less than 70 years, and are set to continue expanding with new stations being built, ageing stations being modernised, and the development of new facilities, such as runways, in progress (Chown, 2018). Until now, decisions on expanding this infrastructure across Antarctica, and its subsequent environmental impacts, have been without the context of how much footprint (the spatial extent of disturbance) is already present. Explicit planning to conserve the natural values of Antarctica from the impacts of research stations has also been largely *ad hoc* (Roura & Hemmings, 2011). The research within this thesis aims to address these issues by: contributing to the understanding of the *footprint* of human activities; investigating what causes contemporary impacts at stations; providing data on the extent of footprint across the entire continent; and suggesting how this information can be systematically used by the international community to better plan for conservation of natural values commensurate with Antarctica's designation as a 'natural reserve' (ATS, 1991).

Background

Until the 19th Century the inaccessibility and hostile climate of the Antarctic protected it as the last untouched continent. Substantial human activity began nearly 200 years ago with the sealing industry in the Maritime Antarctic (Headland, 2009). Permanent infrastructure on the continent then followed, commencing in 1898 with the 'Heroic Era' of exploration, initiating the spread of human footprint across the continent (Headland, 2009). The following 50 years brought with it a gradual increase in the level of development on the continent, but was significantly interrupted by the world wars. Although bursts and pauses of activity in Antarctica occurred, and territorial claims were made, the growth of footprint was small (Brooks, 2018). The 1950s, however, witnessed a turning point in focus on the continent, aided by countries emerging from World War Two equipped with advanced ships, aircraft, and military capabilities. During this decade a build-up of stations and projects culminated with the

1957–58 International Geophysical Year (IGY). This brought international attention to Antarctica, and with it, a massive growth in footprint across the continent. Although geopolitical tensions eased with the ratification of the Antarctic Treaty following on from the IGY, the growth of footprint on the continent has continued to expand since.

The proceeding decades since the IGY have brought a modern era of Antarctic exploration with organised national programs as the main physical presence on the continent; focused on logistical capabilities, increased safety, higher expectations of comfort, and permanent buildings and infrastructure (Brooks et al., 2019; Nielsen, 2013). A consequence of this modern approach has been increasingly complex stations with significantly larger footprints. Adding to this, an increase in international attention on the continent (Dudeney & Walton, 2012) has seen 54 countries accede to the Antarctic Treaty (ATS, 2019a) accompanied with the construction of over 100 facilities in new locations (COMNAP, 2017). These national facilities now accommodate around 4,500 personnel each austral summer and attract a further 30,000 tourist landings (COMNAP, 2017; IAATO, 2017).

Until the 1990s, the priorities for national Antarctic operations were to provide facilities to survive the elements, maintain a national presence, logistical support, and science. Although awareness of the need to conserve environmental values existed (e.g. Carrick, 1960; Hughes et al., 2013), it didn't receive enough attention to prevent activities with substantial impacts from being commonplace. These impacts, primarily within station sites, were both incidental and planned including: open dumping of waste on land and ice (including contaminants) (Fryirs et al., 2013; Goldsworthy et al., 2003; Raymond & Snape, 2017; Tin et al., 2009), overt destruction of habitats for construction (Kriwoken, 1991; Wilson et al., 1990), deliberate and accidental introductions of non-native species (Frenot et al., 2005; Hughes & Worland, 2010; Smith, 1996) and indiscriminate modification of landscapes (O'Neill et al., 2015). These practices continued substantially unchecked until 1991 when an increasing international awareness of the need for environmental protection combined with failing negotiations for mining in Antarctica, leading to the creation of the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol) (ATS, 2019b). The Madrid Protocol provided a framework for the comprehensive protection of the Antarctic environment within the constraints of the Antarctic Treaty structure. It also introduced a step change to how the impacts from human activity were considered; Antarctica was now designated as a 'natural reserve' and protection of the environment was a fundamental consideration. Despite the enhanced protection afforded by the Madrid Protocol, however, substantial impacts to the environment are still permissible within its ambit (Coetzee et al., 2017). Wide-spread pre-Protocol 'legacy' impacts also persist (e.g. Fryirs et al., 2013) due to naturally slow recovery rates, simple ecosystems, the low temperatures of the Antarctic environment (O'Neill et al., 2015 and references therein), and limited capacity (or prioritisation) within national programs to remediate them (Raymond & Snape, 2017) (notwithstanding an explicit requirement to do so [Article 1(5) of Annex III to the Protocol]).

As the sites of the most pronounced human impacts on Antarctica, research stations are distributed across the continent, with accessibility, geopolitical, and research interests the most common determining factors for their locations. The practicality of coastal ice-free land, in particular, is well known to have resulted in it being disproportionately targeted for station sites (e.g. Poland et al., 2003), but the spatial extent of current impacts within these areas has remained unknown. The human impacts on ice-free areas are of particular conservation interest as this land makes up less than half a percent of the continent (Brooks et al., 2019), but provides the essential habitat for most of Antarctica's biodiversity including all bryophytes, lichens, vascular plants, terrestrial invertebrates, most penguin species' rookeries and seabird nesting sites (Bergstrom et al., 2006; Convey et al., 2014). Similarly, they are the only accessible locations to study Antarctic landforms, desert pavements, and fossil sites (Kiernan & McConnell, 2001; O'Neill, 2017). Despite its highly concentrated values, only 1.5% of all ice-free land is formally reserved within Antarctic Specially Protected Areas (ASPAs), justifying concerns in regards to their adequacy for providing long-term conservation (Chown et al., 2017; Shaw et al., 2014; Terauds & Lee, 2016).

One of the main impediments to the effectiveness of current conservation measures has been an ongoing lack of data detailing the extent of human impacts across the continent. This need for data has been well documented (e.g. Abbott & Benninghoff, 1990; Cordonnery, 1999; Summerson & Tin, 2009; Walton & Shears, 1994), but the international-nature of human activity on the continent has made monitoring and reporting of human impacts between Parties inconsistent at best (Hughes, 2010; Jabour, 2009). As a result, limited data on the expanding human development and infrastructure across the continent has been available (Coetzee et al., 2017). For individual research stations, this has meant a relative lack of context, regionally or locally, for how substantial or significant their impacts are on natural values (Jabour, 2009). Consequently, this has limited continent-wide conservation, especially within the restricted yet globally significant terrestrial environment (Poland et al., 2003), from being systematically planned or managed (Coetzee et al., 2017).

In light of the spreading human footprint across Antarctica, and to ensure conservation of the environment is consistent with the Environmental Principles of the Madrid Protocol (Article 3); explicit planning of human impacts and the protection of natural values at individual station sites is required. The first step to support this is developing a spatial understanding of the pressures resulting from station activity. *Footprint* has been a useful term within the scientific literature and Antarctic Treaty fora to describe spatial disturbance, but terminology differences have constrained consistent usage for any widespread application (Brooks et al., 2018; Jabour, 2009). Data availability has been similarly limited, with continent-wide information on the extent of station impacts restricted to dot points coordinates (supported only with limited data such as average populations), or single-location studies, preventing any useful analyses of their implications for broad-scale conservation. By establishing such data, understanding how significant the continent-wide footprint is possible, allowing decisions for implementing conservation planning and management of station sites to be informed in accordance with Antarctica's designation as a natural reserve.

Chapter Overview

The following chapters have been written in the form of five research papers and one dataset. The descriptions below provide the contribution of each chapter towards this thesis:

Chapter 1

What is 'footprint' in Antarctica: proposing a set of definitions. Published on the 13th of June 2018 in the journal *Antarctic Science*.

This paper provides a literature review to base the thesis upon, as well as forming a foundation for using the terminology *footprint* in the proceeding chapters. It also aims to progress environmental protection efforts through developing a common understanding on what *footprint* refers to in Antarctica.

Chapter 2

An analysis of environmental incidents for a national Antarctic program. Published on the 15th of April 2018 in the *Journal of Environmental Management*.

The intent of this paper is to investigate the origins of impacts that contribute to the footprint of a station, and discern whether these are from environmental accidents, or from routine, planned, and cumulative activities. Establishing this information is crucial to inform how to manage activities that result in substantial environmental impacts.

Chapter 3

Our footprint on Antarctica competes with nature for rare ice-free land. Published on the 4th of March 2019 in the journal *Nature Sustainability*.

This paper sets the context for conservation planning across the continent by introducing the first high-resolution spatial dataset capturing the footprint of infrastructure and disturbed ice-free ground for all Antarctica. Through creating these data, identification of information relevant for conservation planning at a continent-wide scale is enabled, including insight into how station layout and the local environment affect how much impact a station has, and its relevance to protected areas and biogeographical regions.

Chapter 4 (Data chapter)

Our Footprint on Antarctica - Buildings, disturbance. Published on the 27th April 2018 in the

Australian Antarctic Data Centre.

During the creation of Chapter 3, substantial data on areas of infrastructure across the continent were collected. In addition to the 5,455 building and 772 disturbance polygons, these data contain further information within their attribute records (not used in Chapter 3). These footprint data are further supplemented with GIS layers including locations of automated weather stations, lighthouses, flight routes, landing sites, maintained traverse routes, camp and hut sites, historic sites and monuments, and sites of current and former stations. The publication of these data provide further information towards continent-wide conservation planning and environmental management, as well as initial footprint layers for any station's operator to conduct conservation planning.

Chapter 5

Insights on the environmental impacts associated with visible disturbance of ice-free ground in Antarctica. Accepted for publication on the 9th of October 2019 in the journal *Antarctic Science*.

This paper builds on the relevance of Chapters 3 and 4, by assessing the effectiveness of visibly disturbed ice-free ground as a continent-wide proxy for further environmental impacts. By doing so, this paper builds on the understanding of substrate-impacting processes in Antarctica, and provides a tool for the rapid assessment of disturbance to ice-free ground.

Chapter 6

Conservation Planning for Antarctic Research Stations. Preprint.

This paper provides a discussion to the thesis by tying together the knowledge gained in the preceding chapters and how it can be applied towards conservation planning for stations. This is achieved through providing an approach to systematic conservation planning tailored to the unique characteristic of stations, supported by an in-depth case study of its applicability to Australia's Casey Station.

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Chapter 1:

What is ‘footprint’ in Antarctica: proposing a set of definitions

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Chapter 2:

An analysis of environmental incidents for a national Antarctic program

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Research article

An analysis of environmental incidents for a national Antarctic program

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ABSTRACT

Research stations in Antarctica are concentrated on scarce ice-free habitats. Operating these stations in the harsh Antarctic climate provides many challenges, including the need to handle bulk fuel and cargo increasing the risk of environmental incidents. We examined 195 reports of environmental incidents from the Australian Antarctic Program, spanning six years, to investigate the impacts and pathways of contemporary environmental incidents. Fuel and chemical spills were most common, followed by biosecurity incursions. The majority of reports were assessed as having insignificant actual impacts. Either the incidents were small, or active, rapid response and mitigation procedures minimised impact. During the period only one spill report (4000 l) was assessed as a 'high' impact. This is despite over 13 million litres of diesel utilised. The majority of incidents occurred within the existing station footprints. The pathways leading to the incidents varied, with technical causes predominately leading to spills, and procedural failures leading to biosecurity incursions. The large number of reports with inconsequential impacts suggest an effective environmental management system with a good culture of reporting environmental incidents. Our findings suggest that the key to continual improvement in an ongoing environmental management system is to learn from incidences and take action to prevent them occurring again, with an end-goal of minimising the residual risk as much as possible.

1. Introduction

Extreme cold, wind, altitude and isolation make Antarctica one of the most challenging operational environments on Earth. Antarctic Treaty nations demonstrate their commitment to protect the Antarctic environment through adherence to the Protocol on Environmental Protection (the Environmental Protocol – Article 3.1). Despite such commitments, human activities and incidences in Antarctica are known to affect biota, degrade the environment and habitat, contaminate substrates, and impact wilderness and aesthetic values (Hull and Bergstrom, 2006; Tin et al., 2009). The potential significance of many environmental incidents increases because Antarctic program activities are focussed in terrestrial areas, which constitute just 0.34% (or less) of the continent (Burton-Johnson et al., 2016; Terauds and Lee, 2016), and most stations are located in the ~0.05% of terrestrial Antarctica within 2 km of the coast (Hull and Bergstrom, 2006). The impacts of contamination and disturbance are compounded further by slow natural recovery rates in the cold environment (Ferguson et al., 2004; Bargagli, 2008; Polmear et al., 2015).

The main forum for reporting environmental incidents associated with national Antarctic program operations is through the Council of Managers of National Antarctic Programs (COMNAP). In 1999, COMNAP released an assessment of environmental emergencies from a voluntary survey of 17 National Antarctic Programs (COMNAP, 1999). During a ten-year period (1988–1998), 133 incidents which had 'potential' to result in adverse environmental impacts or required an emergency response had been reported (COMNAP, 2000). The majority of incidents were hydrocarbon spills (93), predominately of diesel fuel (69) with 30 in excess of 1000 litres (l) (COMNAP, 2000). There were also 10 transport-related incidents where the vehicles/aircraft were irretrievable. COMNAP (2002) updated this assessment with a further 58 environmental incidents reported between 1999 and 2002.

Environmental incidents have continued to occur since 2002. At least 14 vessels have sunk or run aground, including the sinking of the tourist vessel MV *Explorer* in the Bransfield Strait in 2008

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0301-4797/

(Darby, 2010; ASOC, 2012; Baxendale, 2016). The ship was carrying ~210 000 l of hydrocarbons, with an undetermined amount polluting surrounding marine environments. Onshore spills have also continued to occur; some with quantities up to 25 000 l (NZAS, 2003). Hydrocarbon contamination around stations suggest that smaller spills are also common and widespread (Bargagli, 2008; Klein et al., 2012; Raymond et al., 2016). Such contamination is known to impact Antarctic biota and habitat function (Raymond et al., 2016).

Heavy metal contamination is readily detected in substrates around active and abandoned stations (Santos et al., 2005; Bargagli, 2008; Guerra et al., 2013). While more evidence is needed on the direct effects of heavy metal on Antarctic ecosystems (Claridge et al., 1995; Santos et al., 2005; Bargagli, 2008; Guerra et al., 2013), they may have synergistic impacts when combined with hydrocarbon contamination (Stark et al., 2003).

The treatment of waste has improved since the adoption of the environmental protocol by most Antarctic nations. Despite reports of waste dispersal issues now being rare, they are inevitably associated with operational accidents. Within the past 10 years these have included two catastrophic station fires, with known contamination occurring (Russia, 2009; BBC, 2012; Guerra et al., 2013). Remote area aircraft accidents have also occurred, with certain levels of waste deposition (ABC, 2010; AAD, 2013; ATSB, 2015). Near-shore resupply incidents including barges overturning and ships running aground also occur (e.g. Brazil, 2012; AAD, 2016), with a potential for release of waste and pollution (e.g. abrasion and release of anti-fouling treatments into the local environment). There is also ongoing legacy waste associated with the presence of old tip sites and waste management practices from prior to the environmental protocol.

Introductions of non-native species into Antarctic environments have also been reported (Hughes et al., 2009, 2011; Houghton et al., 2014). Research has demonstrated that national program and tourist operations are vectors for non-native species and propagules (Whinam et al., 2005; Hughes et al., 2009; Chown et al., 2012; IAATO, 2012; Houghton et al., 2014). Incursions of non-native flora and fauna are occurring, with increasing ranges into natural habitats (Hughes and Worland, 2010; Olech and Chwedorzewska, 2011; Chwedorzewska et al., 2014). Although most species arriving are outside their climatic range, the diversity of species arriving (Whinam et al., 2005; Hughes et al., 2011; Houghton et al., 2014), and warming temperatures in Antarctic regions (Mulvaney et al., 2012), increases the possibility of establishment (Frenot et al., 2005; Chown et al., 2012; Hughes et al., 2012; Molina-Montenegro et al., 2014; Pertierra et al., 2016; Lee et al., 2017).

Negative impacts on Antarctic vertebrate wildlife have been demonstrated from disturbance associated with general Antarctic program operations (Coetzee and Chown, 2016). Although there has been no evidence of introduced disease (Grimaldi et al., 2010), individual animal deaths (IAATO, 2011a; IAATO, 2011b; IAATO, 2012), the ease of possible transfer (Curry et al., 2002), and discovery of antibodies for common avian disease in wildlife near stations (Miller et al., 2008) have raised concern of the risk (Kerry and Riddle, 2009).

Reports of accidental spatial impacts on the terrestrial environment (i.e. landscape or habitat degradation and expansion of physical footprint) are scarce (Poland et al., 2003), but known to have occurred (Tin et al., 2009). Monitoring of popular tourism landing sites and within the vicinity of stations shows incidental impacts such as compaction of soils and trampling of vegetation (see: Tejedo et al., 2009, 2016; Tin et al., 2009). There is however limited baseline data to distinguish any cumulative increase with new incidents. Despite this lack of evidence, with 267 979 tourism visitor landings in 2015–16, and 109 COMNAP-listed national facilities across Antarctica (COMNAP, 2016; IAATO, 2017), it is expected cumulative incidental impacts occur.

Thus incidents resulting in contamination or disturbance are known to occur, are not uncommon, and impact the Antarctic environment and its values; but how do they occur, how often do they have more than an inconsequential impact, and are they preventable? This paper presents the analysis of the pathways and impacts of contemporary environmental incidents for a large national Antarctic program, and the first overview examination in general since COMNAP (2002). In 2002, Australia became the first Antarctic Treaty party to implement a ISO14001 based Environmental Management System (EMS) for all of its operations (Maggs, 2002). As part of the systematic approach to environmental management under its EMS, the Australian Antarctic Division (AAD) developed an online reporting system (Incidents, Hazards and Improvement Suggestions Reporting System -IHIS) to aid the continual improvement of its operations. Staff are required to log incidents and near misses regardless of size. This reporting culture provides a sizable dataset to analyse. Here we examine six years of data from this system looking for trends in the cause of environmental incidents and lesson learned that might be valuable for Australia and other operators in Antarctica.

2. Materials and methods

The AAD introduced IHIS, an intranet-based system, to log incidents, near misses, and improvement suggestions. Within IHIS an environmental incident is defined as 'an unexpected occurrence that has had, or could have, an adverse effect on the environment'. Each IHIS report activates a tiered response and subsequent corrective actions (See Fig. 1). The intent of IHIS within the EMS, is the fast reporting of information to allow timely mitigation action, as well as enabling the review of existing practices to prevent future occurrences across all operations.

IHIS reporting is required as soon as practicable following an incident (Fig. 1). Each report in IHIS initially captures the type of incident, details about the incident, location, and initial description of impact (if applicable) directly from the people engaged in the activity in which an incident has occurred. After submission, each IHIS report is classified by type (incident, near miss or improvement) and given two ratings; first on potential and then actual level of impact by AAD's environmental managers. The incident's features are also reviewed against quantifiable parameters (for example: litres of fuels spilled), and within a qualitative consequence scale (Table S1) to derive an impact rating. Impact ratings range from NI (no applicable impact), through Insignificant, Low, Medium, High, to Critical. We reviewed data on environmental incidents from these reports occurring between 31 December 2009–18 February 2016 (6.2 years).

One hundred and ninety-five reports of incidents occurring across the four Australian Antarctic and sub-Antarctic stations, as well as *en route* post-quarantine biosecurity incursions detected at sea, were examined. Reports of near misses with no actual impact were not examined. Twelve reports were contemporary impacts from incidents occurring prior to the review period. These reports were included for their cause, but separated (marked *historic*) for their impact data to delineate them from incidents occurring during the review period. We classified the incident reports along the following categories: biosecurity incursion, bird strike, fuel/chemical spills, waste, wildlife disturbance, and footprint (spatial disturbance impacts).

Additional supporting data of fuel/chemical spills were also compiled including estimated spill quantity data from an existing unpublished review (Frost, 2013) and unpublished data. Estimates were not available or applicable for some incidents. Incident

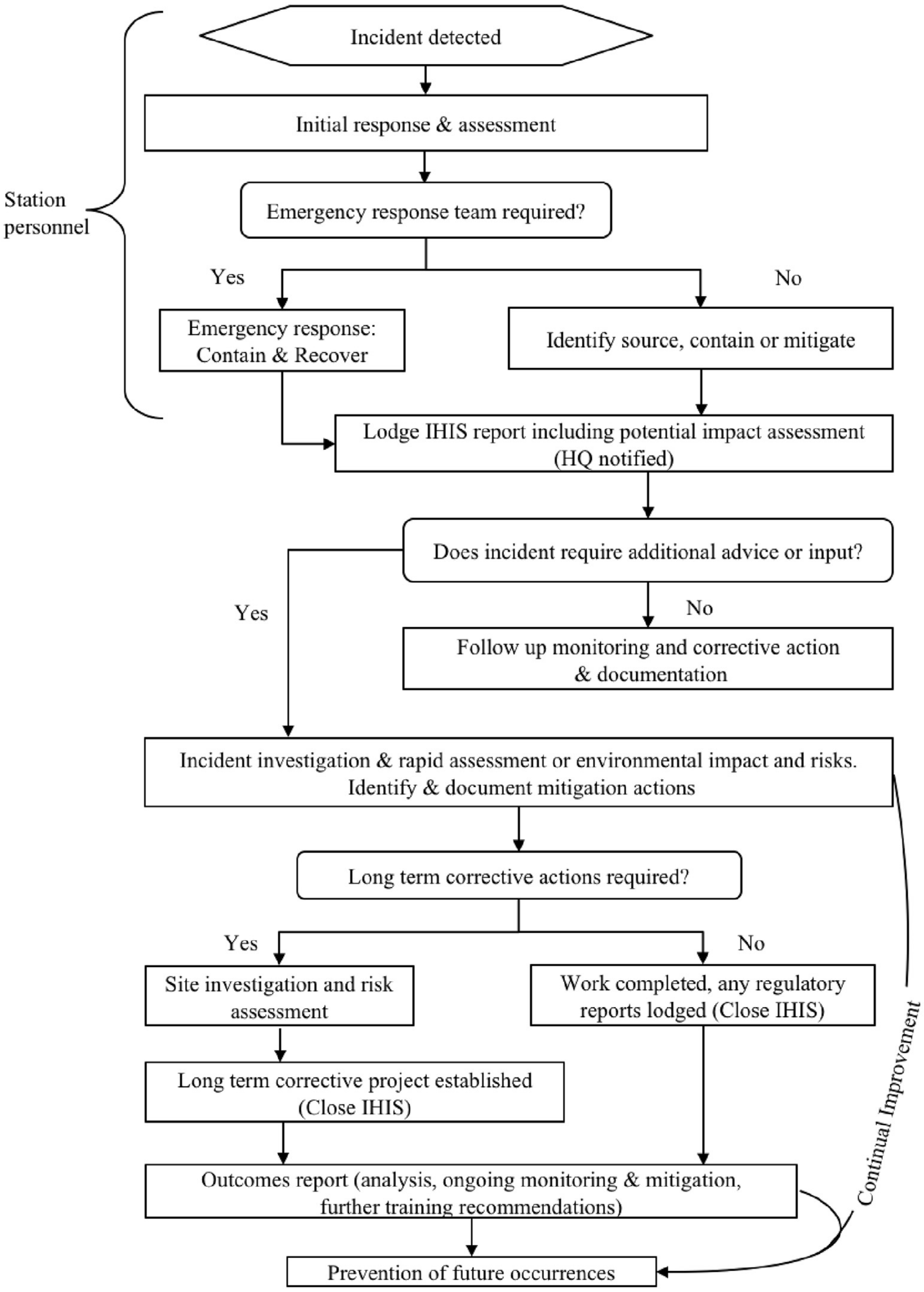

Fig. 1. IHIS Response flow chart.

reports with estimated quantities were merged into the dataset to enable analysis of the fuel/chemical spills. Data on fuel quantities used by the main station plant and equipment (vehicles, boilers, incinerators, and generators) during the review period at the stations were compiled from Australian Department of the Environment *State of the Environment Reporting* Indicators 56, 57, and 58 (fuel usage of generators and boilers, incinerators, and vehicles respectively) (Ratcliffe, 2001, updated 2014; Ratcliffe et al., 2001, updated 2014b, a). These were accessed and retrieved from the Australian Antarctic Data Centre (data.aad.gov.au).

To develop an understanding of probable cause we categorised each incident into either physical *operational* failures, or *procedural* failures. From these two broad categories, five suggested primary causes were developed to provide informative pathways. To allocate a primary cause to an incident, a key criterion differentiating each cause was given, followed by a series of guiding criteria (Table 1). These were intended to assist avoiding semantic differences between the causes. Each incident report was then assessed against these criteria to determine their suggested cause. Pathways identifying potential trends were defined and possible actions to avoid future recurrences were identified.

Incident reports were collated by classification, level of impact

Table 1
Incident-cause selection criteria.

Cause	Fundamental Criteria	Supporting Criteria
Failure of process	*Processes exist, were implemented, but didn't prevent.*	Sufficient application/diligence of process. Process ineffective/insufficient. Insufficient resourcing to effectively apply procedures. Process effective – downstream. Unexpected pathway or outcome. Program's contractors failed process. Unforeseen changes in logistics.
External to program's processes	*No existing process in place to prevent.*	Unforeseen/unpredictable event. Plausible but not practical to prevent. Process possible - not yet created. A result of a third party's actions. Historic cause (procedural or operational). Event of nature.
Failure of plant and equipment	*Unforeseeable failure.*	Preventative measures not practical. Possible to reduce, but prohibitive to eliminate. Caused by adverse conditions.
Failure of maintenance	*Foreseeable failure.*	Preventative measures possible. Failure due to normal wear. Could have been reasonably prevented.
Operator error	*Operator failed to follow established procedures.*	Failure of workmanship. Failure to apply pre-existing processes. Insufficient application/diligence of process. Due to inattention.

and suggested cause, and then where the incident occurred. This was included to indicate the contribution of incidents to the overall cumulative impact within an Antarctic station area. All reports were assessed whether they occurred within the immediate station footprint or the broader associated operating area. This information was then used to provide the proportion of incident reports occurring within the station areas.

Case studies were included to further examine the process and response to incidents.

3. Results and discussion

Given the logistics, harsh conditions, quantities of equipment, personnel and fuel transported by the Australian Antarctic program, very few environmental incidents resulted in substantive environmental impacts. There were also no 'Critical' rated incidents over the six-year study period (Table S1).

There were 14 bird strikes reported with static objects (poles, antenna, and tensioned cables), windmills (both turbines and measuring instruments) and a helicopter. Unfortunately bird strikes are an expected impact of aerial infrastructure (Manville, 2005; Drewitt and Langston, 2006). The environmental impact assessment for the Mawson Station wind turbines identified birds striking the rotating vanes as a risk (Riddle in Kerry and Riddle, 2009). Bird strikes are difficult to completely mitigate against, but because of the crucial role these structures provide in Antarctica, rationalisation and reengineering of aerial infrastructure on Antarctic stations may reduce the risk (e.g. Longcore et al., 2008). A further two wildlife incidents involving curious elephant seals interacting with station infrastructure on Macquarie Island occurred. As clarity exists as to the cause of these 16 incidents, they are excluded from the remainder of the discussion.

The suggested cause of the remaining 179 incident reports varied, with *Failure of Process* providing the highest proportion at 44% (79) of total incidents. *Failure of plant and equipment* came next at 20% (35), then *Operator error* 17% (30), and *Failure of maintenance* 11% (20), and *External to the Australian Antarctic program's processes* at 8% (15). Divided by broad classification the causation varied, *Failure of plant and equipment* was the major contributor to fuel/chemical spill incidents, whereas *Failure of process* was the major contributor to waste and especially biosecurity (Fig. 2).

3.1. Fuel and chemical spills

The Australian Antarctic program has had a long-term focus on hydrocarbon contamination and remediation research initiating with Kerry (1993), thus we anticipated (and found) a high level of diligence in reporting spills. Indeed, most fuel/chemical spills were of small quantities. On the reports in which quantities were recorded (47/79), 50% were less than 10 l, and 85% were less than the COMNAP (2008) reporting requirements (>200 l). The small volumes corresponded with 75% of IHIS reports having no (NI) or insignificant actual impacts. Although fuel spill mean estimated quantities were skewed by large, outlying events median values were low: diesel fuel 1013 l (7.5 l median), drummed fuel 99 l (15 l), glycol 9 l (5 l), hydraulic fluid 3 l (2 l), and lubricating oil 1 l (0.5 l). This is encouraging because 13 278 817 l of diesel was used across boilers, generators, incinerators and vehicles over the time period examined (Ratcliffe, 2001, updated 2014; Ratcliffe et al., 2001,

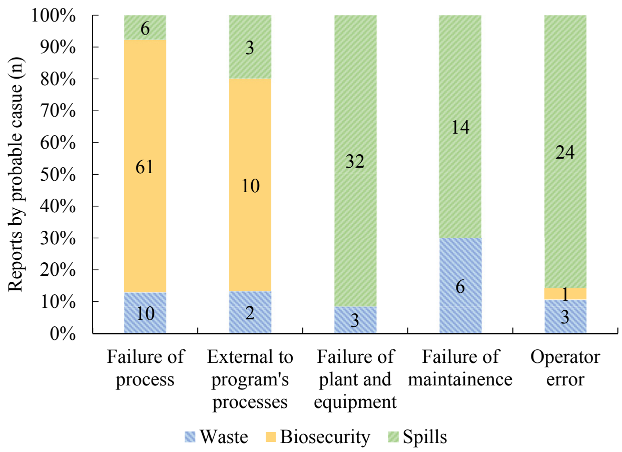

Fig. 2. Number of total incidents broken down into probable cause (wildlife and footprint incidents excluded).

updated 2014a, b). This demonstrates relatively successful fuel handling and storage. However, of the remaining 25%, 6% (5) of spill incidents were rated as having Medium or High actual *impact* (see case studies below).

Four medium and one high spill incidents occurred during the period we examined. Four of these are further detailed in Hayhow (2013); McWatters et al. (2016); Raymond et al. (2016), with the remaining report initiated due to detecting historical hydrocarbon contamination at Macquarie Island; the exact source of this contamination has not been determined. The high rated spill, caused by operator error, occurred at Casey Station in 2015, directly upslope of a previously remediated medium spill from 2012 (see Raymond et al., 2016). This spill contaminated about 800 m^2 of soil with over 4000 l of fuel, as well as the recontamination of an area already being remediated (McWatters et al., 2016). Active mitigation of the spill occurred on discovery utilising expertise developed from the previous spill, including pioneering reuse of bio-remediated soils as backfill during the clean-up (McWatters et al., 2016).

Of these five medium/high spills, only one occurred outside the station precinct. A 600 litre spill occurred within the catchment of Lake Dingle, a hypersaline lake frequented by wildlife and of scientific interest in the Vestfold Hills, when a helicopter needed to jettison a load of three fuel drums to maintain stability (Raymond et al., 2016). Due to the location of this spill, mitigation was particularly resource and labour intensive with 168 tonnes of soil excavated and moved to station by helicopter for remediation (Raymond et al., 2016).

During the six-year period, diesel fuel incidents made up 57% of the 79 spill reports, with the remaining spread across other fluid types (Fig. 3). This is 17% lower than found collectively by COMNAP (2000). The diesel losses were also just 0.07% (9751 l) of the total consumed during the period (13 278 817 l). There was also no known ship to shore refuelling incidents; generally considered the most hazardous activity by the program. This potentially indicates progress in fuel handling since the COMNAP survey and the release of their advisory *Fuel Manual* (COMNAP, 2008). Furthermore, it reflects a shifting focus from large spills (as they reduce in number) to small scale incidents that in many cases are hard to eliminate entirely and are well reported within the Australian program (noting the COMNAP diesel proportions may be affected by operators only reporting larger quantity spills).

The causes this study allocated to all spill incidents were dominated (88%) by operational factors: operator error, failure of maintenance, and failure of plant equipment; where equipment was not operated correctly, was insufficiently maintained, or something had broken (Fig. 2). COMNAP (2000) also reported spills as operational failures, with 51% human error and 49% mechanical failure, but did not consider them in the context of procedural failures.

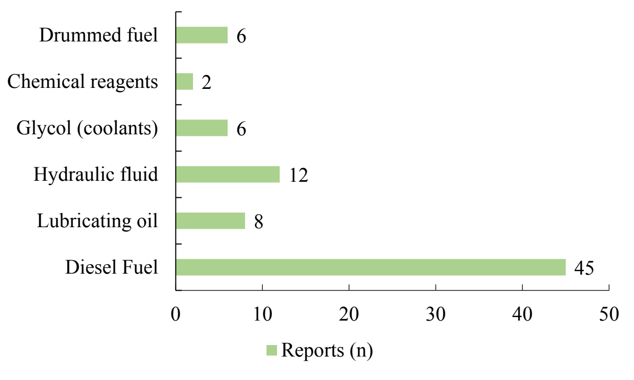

Fig. 3. Number of fuel/chemical spill reports by fluid type [modelled on figure in COMNAP (1999), noting this figure includes spills below COMNAP reporting requirements].

A number of inherent properties of fuel handling and use in Antarctica lead to operational factors being the primary cause of fuel-based environmental incidents. First is the large volumes of fuel/chemicals handled in varied ways increases the likelihood of operational errors, second is the immediate dispersals of fluids into the environment as not all transfer and storage infrastructure can be contained within bunds. For example, 12 incidents were hydraulic fluid leaks from ruptured lines on large vehicles, which are unpredictable and likely to occur outside of contained areas. If fuel/chemical spill incidents for other programs reflect the causes found in Fig. 2, initially targeting improvements to reduce plant/equipment failures and operator error through timely replacement of equipment and improved training may provide the greatest return. However, it worthy to consider that is not always possible to avoid incidents through a maintenance program. Maintenance of aging infrastructure become increasingly difficult and not all failures can be anticipated and thus included in a maintenance program. The extreme environmental conditions can present unexpected problems in equipment which will not be flagged until it occurs.

In the 79 fuel/chemical spill reports examined, 65 were rated as potential to be greater than insignificant (i.e.: low, medium, and high impacts), but only 14 were reported by environmental managers as having those actual impacts. Two key reasons explain this discrepancy. The first is these reports included spills within bunded areas that were entirely contained. The second is immediate response and mitigation action have prevented many spills from causing environmental harm, through the use of spill kits or the complete removal of spills if they have been contained within small volumes of snow. This minimisation may be attributable to measures developed through the AAD's EMS and the COMNAP Fuel Manual (2008).

In response to these and other spills, as well as meeting the general goal of improved environmental performance, the AAD has conducted internal and commissioned independent reviews of fuel handling. In addition to the environmental damage the larger spills have cost the program substantially in terms of on-ground clean-up and remediation, as well as in-direct costs in displacement of scientific research and loss of opportunity. From the reviews, ongoing improvements to address the types of root causes identified in this study are now in place including replacing risk-prone infrastructure as well as updating and implementing a range of procedures and administrative measures. This reflects an active process in improved environmental management aligned with the principles of an EMS.

3.2. Biosecurity incursions

Concern for Antarctic biosecurity has gained increasing prominence since the 1991 environmental protocol. There has been substantial growth in knowledge of the field (e.g. Frenot et al., 2005; Chown et al., 2012) as well as the development of, and adaptation of biosecurity measures (Hulme et al., 2012; Hughes and Pertierra, 2016). Over the last two decades, the AAD has supported research, the development of mitigation methods and culture change in its organisation. Screening of cargo has occurred since 2002 (Whinam et al., 2005), a state-of-the-art cargo and biosecurity facility, with associated procedural changes, opened in 2013 (Australia, 2013), an organisation-wide agreed approach to biosecurity was adopted in 2014 (AAD, Internal report 2014), and the AAD played a role developing the Committee for Environmental Protection's *Non-Native Species Manual* (CEP, 2016). Furthermore, the AAD has had the additional impetus for heightened biosecurity awareness, procedures, and facilities to secure the A$25 million public investment in the successful Macquarie Island Pest Eradication Program (Australia, 2014). Of particular focus has been the prevention of re-introduction of rodents to Macquarie Island through its activities.

Most biosecurity incursions with the IHIS reports (50 from 72) were detected in controlled indoor environments, such as invertebrates in foodstuffs followed by mitigation (removal), thus demonstrating a continuum of vigilance and action beyond the pre-departure quarantine procedures in Australia. These incursions were also relatively rare; with over 105 tonnes of food transported to the Australian stations in the 2016/17 season (N. Tennant, Personal Communication, 13/7/2017). Ninety-four percent of these incidents were assessed as actual low impact or less (Fig. 4), however 40% of incidents presented a medium or high potential impact, due to the risk of establishment in local ecosystems. An example of this is the 2014 detection of non-native collembola within a hydroponics facility at Davis Station, most likely introduced on growing media and thus undetected in the procedural biosecurity screening processing (failure of process) (Australia, 2017). The rapid response following detection and IHIS reporting of this incursion hopefully has prevented the establishment of the species in the natural environment (Bergstrom et al. in press). The majority of biosecurity reports (71 of 72 incidents) were procedural failures in the initial steps of cargo preparation and transport (Fig. 2). However that they were found, indicates that the final step of biosecurity procedures, early detection, was achieved. Furthermore many IHIS reports were detections of dead non-native species. Dead insects, for example, may have been killed by treatment such as fogging during cargo process.

The heightened state of awareness is reassuring, but the effectiveness and difficulty in achieving 100% effectiveness of those procedures for a large Antarctic program means there will be pathways for these incidents to continue to occur (see also Houghton et al., 2014). The placement of multiple barriers to non-native species is probably the most effective way to mitigate this risk and these include high levels of biosecurity awareness and vigilance on stations by all personnel to ensure early detection and rapid response to any incursions (e.g. Bergstrom et al., 2017).

3.3. Waste dispersal

Waste dispersal only constituted 13.5% (n = 24) of total incident

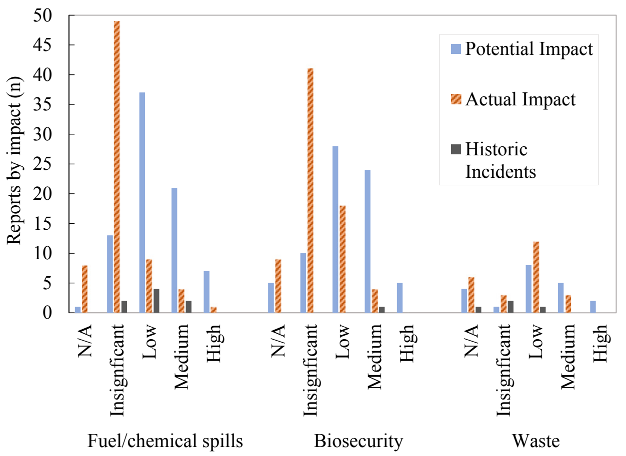

Fig. 4. Level of impact reported from individual incidents, noting 'potential' and 'actual' are listed concurrently.

reports during this period (Fig. 2.). This is contrasting to historic waste; which has been estimated to present a similar scale of contamination as hydrocarbons in the Antarctic environment (Snape et al., 2001). The low number of reports may be attributed to improved awareness, policies, and procedures around cleaning up waste (COMNAP, 2013). Waste dispersal incidents may also be perceived as having less immediacy compared to spills, or go unnoticed, or just not occur as often as other types of incidences.

Waste reports had the least difference between the reported potential and actual impacts of all classifications (Fig. 4). Furthermore, the proportion of incidents incurring an impact greater than *insignificant* was two times higher than biosecurity, and three times of fuel/chemical spills, demonstrating waste dispersal as a genuine pathway for environmental impacts.

The underlying causes of waste incidents reflected the range of materials, with a distributed spread across the causes equally split between operational and procedural (Fig. 2). The highest contributing cause was *failure of process (inappropriate or inadequate storage of material),* at 42% of reports. The incidents involved a range of materials, with a bias towards drums and plastic wrapping and covers. Reports commonly involved waste dispersal due to unexpectedly adverse weather or failure of securing fasteners. A current AAD waste management project is focused on range of operational changes, further procedural implementation, and improved cultural awareness of the issue to reduce further waste dispersal incidents from occurring.

3.4. Other incidents

Incidents with a primary impact of an unintentional expansion of the footprint of stations were only reported on four occasions. These included undesirable placement of storage and track formation. We acknowledge other forms of impact reported (i.e. contamination, waste dispersal) also contribute to a station's footprint (see: Brooks et al., in press). The four disturbance footprint incidents were rated as NI (2), low, and high actual impacts, with two attributed to *failure of processes*, and two for *operator error*. These were omitted from the figures due to the low number. Given the cumulative nature of disturbance footprint, and the limited literature on landscape disturbance in Antarctica (see: Tin et al., 2009), it is expected further expansion has occurred. Assessing a station's footprint baseline, such as Brooks (2014), may prompt operational awareness, as well as enabling further detection of such incidents.

3.5. Incident locations

Incidents occurred within station limits for the large majority of reports; 73% of total, (divided by classification: 73% of fuel/chemical spills, 78% of biosecurity, and 67% of waste reports) occurred within this area. The remainder occurred within the broader operating areas associated with each station and reflects the hub and spoke model of human activities in Antarctica (Hull and Bergstrom, 2006). As station limits are the focal point of Antarctic activity, the majority of incidents occurring within them is expected. The location of these incidents are important, as on-station incidents may add to, or be undetectable above, the existing long-term disturbance footprint of the stations. The minority of incidents on the periphery or external to station limits, however, have the potential to expand the footprint of Antarctic operations. Although this dataset did not contain sufficient information to quantify the footprint of these incidents, it does draw attention to a heightened risk to the environment for field activities.

4. Conclusions

These results show small scale environmental incidents have continued to be relatively common in the Australian Antarctic Program since the COMNAP (1999) survey. Although this was expected due to the challenges of Antarctic operations, this analysis of incidents associated with a large national program should assist other Antarctic operators in meeting their objectives and obligations under the environmental protocol. Incidents are generally caused by a number of mechanisms, but there were distinct pathways for the two highest reported incidents: fuel/chemical spills and biosecurity incursions. The pathways of fuel/chemical spills occurred due to *operational failures*, while most biosecurity incidents were consistently *process failures*, with processes either not fully implemented or not yet created. The pathways that led to fuel/chemical spill incidents, primarily operational failures, are technical in nature due to their reliance on equipment for prevention, with a range of measures required to reduce them further, including improvements in quality and design of manufactured equipment for use in Antarctic environments.

In the case of biosecurity, although the processes technically failed as non-native incursions occurred, process-driven awareness has also led to early detection and eliminated actual impact at the stations. Just two known non-native species establishments were detected during this period; both on Macquarie Island, which is under the jurisdiction of the Tasmanian government and therefore outside the direct control of the AAD (Pertierra et al., 2016, DPIPWE & University of Queensland unpublished data). Reduction in further process failures may be achieved by regular review and audits of procedures for effectiveness and achievability, and further training and awareness for the operator's staff and their suppliers.

Fuel and chemical spills in these reports had the most impacts on the environment through quantity and severity. Fuel spills are a dominant source of pollutants at all stations (Bargagli, 2008) and this result supports the body of work on the risk of spills in Antarctica, as well as the AAD's dedicated remediation research. Although the current climatic gradient has mostly provided protection up until recently from non-native species impacts, biosecurity incursions are an emerging threat to the region, and national programs are a proven unintentional vector for intercontinental translocation (with the exception of the sub-Antarctic) (Chown et al., 2012). We recognise that major non-natives species incursion, potentially can alter ecosystems permanently and recommend that all Antarctic programs should take measures to ensure the risk is appropriately addressed.

Incidents contributing to the expansion of the disturbance footprint are expected to occur more often, but may not be recognised as an 'incident', or there are no means currently for it to constitute an incident (i.e. incomplete footprint baseline measurements). In the case of these findings it is suggested, with the exception of spills and fuel contamination, environmental incidents in the Australian Antarctic Program over the six years studied have contributed to an existing cumulative environmental impact but play a smaller role than the footprint from planned activities and pre-environmental protocol practices.

The results found by this study were derived from reports made by Antarctic expeditioners. As such, the data is indicative (rather than robust) of what is occurring, and more importantly, what expeditioners are aware of and therefore are more likely to detect and report. The reporting of 119 insignificant incidents during this period indicates that operators have high awareness of the IHIS system. This culture of awareness, and emphasised no-blame approach, is important in preventing major incidents, but increases the overall number of reports. This awareness may also be heightened in less disturbed areas away from station limits, disproportionately increasing off-station reports. These reports are also vulnerable to what an individual or organisation considers an incident.

4.1. Future directions for improvement in environmental stewardship

The use of an incident reporting system, as part of an EMS, has demonstrated that expeditioners working in the Australian Antarctic program have a high level of environmental awareness. Underlying cause analysis allows managers to focus on pathways to reduce the number of further incidences (repeat occurrences), acknowledging while some pathways may require a straightforward change, others may be highly technical and cost prohibitive. All categories examined (failure of process, external to programs processes, operator error, failure of maintenance, failure of plant and equipment) can be incrementally improved through a hierarchy of controls to address risks by looking at elimination, substitution, engineering controls and administrative controls. While this approach is more commonly applied to hazards and safety it is also useful when investigating the underlying cause of significant environmental incidents. The key to continual improvement in an ongoing environmental management system is to learn from incidences and take action to prevent them occurring again with an end-goal of reducing the residual risk to as low as possible. This is an ongoing process at the AAD. That even small incidents are being recorded suggests that a good environmental protection culture is also well established with the Australian Antarctic Program and this analysis provides a baseline for future comparisons. Analysis of incidents is an inherent component of the AAD's operations and its EMS and is intended to support continually improved maintenance and replacement schedules.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this chapter can be found at https://doi.org/10.1016/j.jenvman.2018.02.024.

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Chapter 3:

Our footprint on Antarctica competes with nature for rare ice-free land

nature sustainability

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Our footprint on Antarctica competes with nature for rare ice-free land

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Construction and operation of research stations present the most pronounced human impacts on the Antarctic continent across a wide range of environmental values. Despite Antarctic Treaty Parties committing themselves to comprehensive protection of the environment, data on the spatial extent of impacts from their activities have been limited. To quantify this, we examined the area of building and ground disturbance across the entire continent using geographic information system mapping of satellite imagery. Here, we report the footprint of all buildings to be >390,000 m², with an additional disturbance footprint of >5,200,000 m² just on ice-free land. These create a visual footprint similar in size to the total ice-free area of Antarctica, and impact over half of all large coastal ice-free areas. Our data demonstrate that human impacts are disproportionately concentrated in some of the most sensitive environments, with consequential implications for conservation management. This high-resolution measurement of the extent of infrastructure across the continent can be used to inform management decisions to balance sustainable scientific use and environmental protection of the Antarctic environment.

Antarctica is the world's largest natural reserve, and the Antarctic Treaty System requires participating countries to monitor the impacts of their activities[1]. Construction, operation and abandonment of research stations in Antarctica currently cause the most prominent human impacts on a wide range of environmental values[2]. Recent research attention into how humans impact the continent has focused on threats from non-native species, climate change and contaminants[2–5], but there has been limited consideration of the expanding development of infrastructure[6,7]. To address this gap, we used geographic information system (GIS) mapping of satellite imagery from 2005–2016 to create the most accurate spatial dataset of human pressure across the entire Antarctic continent. The footprints of buildings[8] across all regions were measured, along with surface disturbance to ice-free land, due to these rare areas of the continent supporting the highest taxonomic and ecological diversity, and being essential habitat for iconic species such as Adélie penguins[9,10]. As we anticipate a future expansion of human impacts[7,11,12], spatially explicit information on such threats is crucial for Antarctic Treaty signatories to sustainably protect the Antarctic environment within a systematic conservation framework[6], while maintaining access to these areas for science. This information has multidisciplinary consequences, and can be used to inform conservation decision-making for improved environmental management, encourage coordinated sharing of facilities[13], and track impact and change.

The term 'footprint' is defined here as the spatial extent of human activities and associated impacts. Footprint in Antarctica can take many forms[8] with the most significant being the long-term physical modifications to terrestrial ice-free substrates and habitats ('disturbance footprint') and the placement of buildings and infrastructure across the continent ('building footprint'), including stations, runways, field huts, historical structures and abandoned sites, waste and tourist camps. Associated with these are a spectrum of pressures, including sewage discharge, hydrocarbon and heavy metal contamination, noise and visual impacts[2,8], which can all impact on Antarctica's ecological, intrinsic and scientific values. The paradox here is that these impacts, mainly attributed to supporting access for science, may conflict with the need to preserve untouched environments for research use as well as conservation commitments.

The cumulative growth of building and disturbance footprints in Antarctica began in 1899 with huts built by the heroic era explorers such as Scott and Shackleton. However, substantial expansion only began in the 1950s, initiated by the 12 original signatories to the Antarctic Treaty[14] before the Treaty entered into force in 1961. This growth has continued to increase, augmented by a further 41 new signatories and a traditional expectation that building a station was required to gain decision-making Consultative Party status[15]. The current framework for comprehensive protection of the Antarctic environment is provided by the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol)[1], adopted in 1991. Before this, practices such as local dumping of waste (including hydrocarbons) and limited environmental assessments were common. Importantly, two-thirds of current stations were established before the adoption of the Protocol, with contemporary measurements of footprint reflecting this legacy.

The Madrid Protocol aims to protect the Antarctic environment, its dependent and associated ecosystems, and its values[1]. Although some values are present across the whole Antarctic continent, such as those associated with ice sheets and glaciers, the small ice-free 'islands', spread across isolated coastal oases, mountain ranges and nunataks, are a habitat for the majority of terrestrial species[16,17]. The coastal fringes of these areas are particularly important as they typically provide the best environmental envelope for flora and fauna[18], and accessibility for terrestrial-breeding marine vertebrates. Ice-free areas are also the most accessible locations for studying Antarctic landforms (for example, fossils, soils and geomorphology)[19], further increasing the scientific value of these small areas[18]. We calculated the current total ice-free area of Antarctica to be 0.44% (54,274 km²) and found 81% of all buildings to be within this diverse[10] environment (see Methods for background on this increased ice-free area estimate, up from 0.18–0.38%[20,21]). Indeed 76% of all buildings are situated in just 0.06% of Antarctica—the accessible ice-free areas

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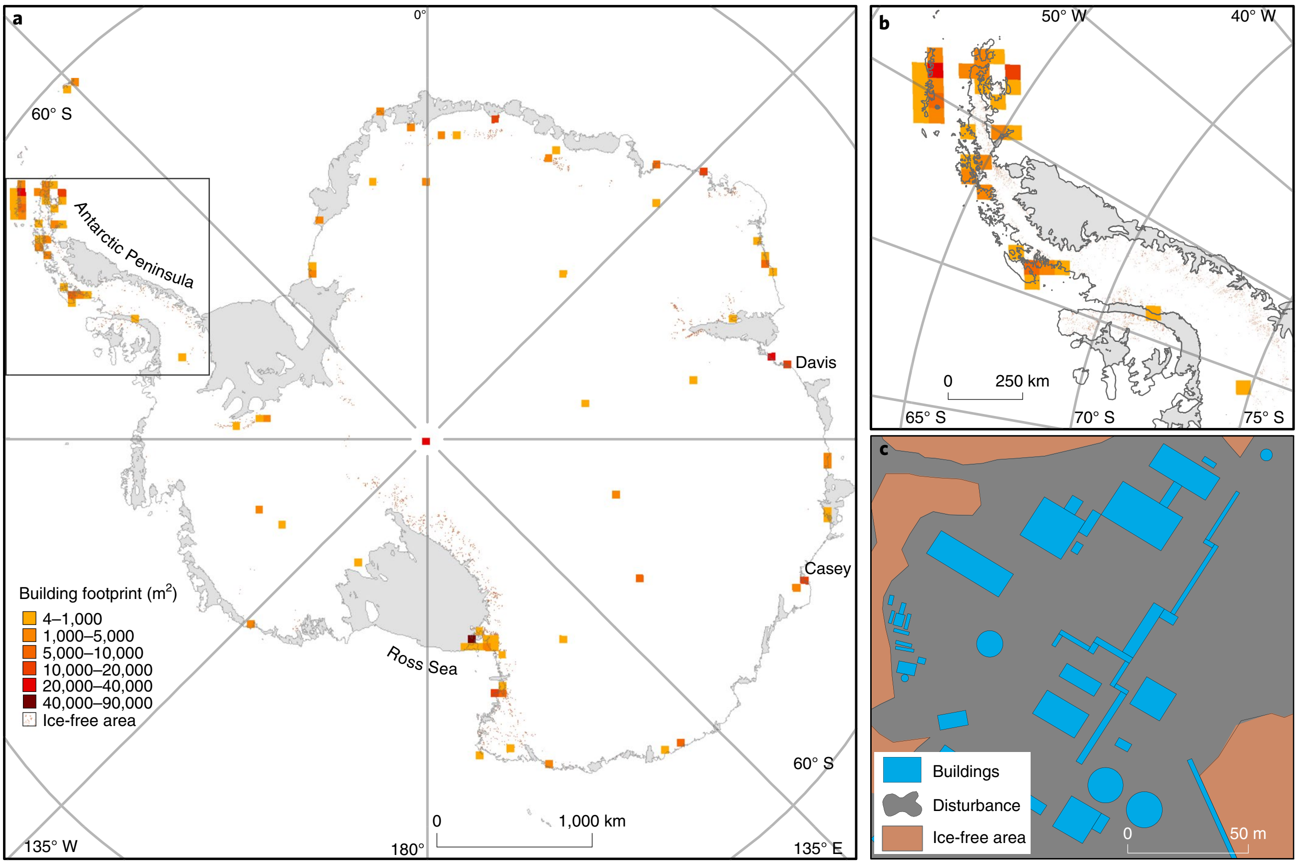

Fig. 1 | Distribution of the building footprint on Antarctica. a, Distribution and density of the building footprint represented within 50 × 50 km^2 cells. These cells may include multiple stations. **b**, Density of the building footprint within the Antarctic Peninsula—the area acknowledged as the most developed and vulnerable to threats from climate change and non-native species. **c**, Example of the detail applied, showing the buildings and disturbance footprint mapped within Australia's Davis Station.

within 5 km of the coast—clearly indicating that human impacts are disproportionately concentrated on the most environmentally significant areas of Antarctica.

Using GIS digitization of active and abandoned structures observed within satellite imagery (captured between October 2005 and December 2016 (median: December 2011)), we mapped 158 locations with 5,342 individual vector-based 'building' polygons across Antarctica on both ice-covered and ice-free environments (Fig. 1). The total building footprint across Antarctica was 0.393 km^2 (Supplementary Table 1)—an area equal to 73 USA football fields—higher proportions of which were located within two hotspots of activity centred on coastlines of the Antarctic Peninsula and Ross Sea. Although 30 signatory countries contributed to this total area, 3 accounted for the majority (54%).

As aesthetic and wilderness values are given the same protection under the Madrid Protocol as scientific significance, we considered the visual footprint of buildings on the Antarctic landscape (Fig. 2). By applying a range of buffers according to the visible distance of Antarctic infrastructure[22] (20 km (planar) for stations, 10 km for abandoned stations and field camps, 5 km for refuges and field huts, and 5 km for automatic weather stations, historic sites and monuments), we estimate the total visual footprint to extend up to 93,500 km^2 (including offshore visibility). When confined to onshore areas, this footprint is 58,500 km^2 (or 0.48% of Antarctica)—a size similar to but larger than all ice-free areas on the continent. Station buildings contribute to 90% of this visual footprint. Although the areas shown here are considered to be the maximum visibility, and would be affected by factors including topography, the current visibility modelling that we have used[22] excludes surface modifications such as roads, runways and maintained traverse routes, which may increase this estimate once their viewshed is established.

The total disturbance area within ice-free environments from human activities was 5.242 km^2 (Supplementary Fig. 1). This equates to nearly 1,000 football fields, or 1,135 m^2 of disturbed ground for every person at an Antarctic research station (at peak capacity)[23]. We found that some disturbance was present in more than half of all large ice-free coastal areas (>50 km^2; <5 km from the coast; n = 15/29). Again, three countries contributed the majority (53%) of all detectable disturbance. Here, only visibly observed disturbance was mapped (for example, roads, levelled areas and spoil piles), with further below-detection levels of disturbance expected due to the limitations of satellite imagery resolution[24], resulting in this probably being a cumulative underestimate (see the section 'Sources of error'). This total disturbance figure also excludes naturally and artificially remediated ground (for example, the former Hallett Station site) where impacts associated with disturbance may still persist (for example, refs. [25,26]). While physical disturbance of ice-free ground does not guarantee negative biological impacts, there is evidence of detrimental effects from an increasing number of Antarctic environments and associated biota[27–29] threatening natural processes that have been ongoing for millennia. Furthermore, disturbance to ice-free areas is known to affect geomorphological, aesthetic and wilderness values[30–33], and is associated with activity that can disturb wildlife[34].

Fig. 2 | Modelling of the visual footprint of Antarctic infrastructure. Maximum visual footprint of Antarctic buildings in scale, applying visibility modelling by Summerson[22]. Even with conservative buffers applied at half the distances suggested by the modelling, the footprint still covers 26,400 km^2 (16,500 km^2 onshore only). While visibility distances are yet to be established for maintained traverse routes (shown here), they cover an estimated 6,169 km in distance, which would add over 12,000 km^2 to this footprint if visible from just 1 km.

Continent wide, the median disturbance-to-building-footprint ratio for facilities in all ice-free areas was 12:1 (mean 21:1; range 2:1–178:1). Several factors have contributed to variations in the disturbance footprint. Station configuration had a clear effect: decentralized stations, with their buildings dispersed over a relatively large area, often have evidence of extensive road networks, while others have terrestrial runways situated away from the main station buildings (older stations, in particular, were deliberately dispersed for safety to ensure protection from fires spreading between buildings). Decentralized stations had disturbance ratios more than twice as large as centralized stations (that is, a larger disturbance footprint for the same overall building area; mean = 6.85:1 for centralized and 17.0:1 for decentralized; $P < 0.001$).

The effects of substrate and station size were less clear, with some aspects being inconsistent across different but equally plausible models (see 'Statistical Analysis' and Supplementary Information for model details). Within ice-free areas, certain substrates are known to be vulnerable to disturbance[35,36], increasing the likelihood and rate of substrate modification[31], and enhancing its detectability within remote-sensed imagery. Additionally, the majority of stations are located in soil/gravel sites ($n = 60$) rather than rock outcrops ($n = 17$). The characteristics of softer soil environments mean they are readily utilized in earthworks and road construction, which, when combined with environmental legacy impacts[31,35,36], has resulted in these locations typically having an enlarged disturbance footprint. Our data showed that centralized stations located on soil substrates had 70% higher disturbance-to-building-area ratios compared with those located on rock (range 43–111% across the 4 plausible models; see Supplementary Information). However, based on the data available, it was not clear whether substrate also had an effect with decentralized stations, nor whether the disturbance ratio varied by station size.

The biogeography of ice-free terrestrial Antarctica has been categorized into 16 Antarctic Conservation Biogeographic Regions (ACBRs)[10,20], with each ACBR being a biologically and geographically distinct region. Half of all the terrestrial disturbance we quantified occurred in just two of these ACBRs—South Victoria Land and the Northwest Antarctic Peninsula (Supplementary Table 2). The Northwest Antarctic Peninsula is recognized as part of the most biologically diverse area of the continent[18]. Two other ACBRs (Adélie Land and East Antarctica, known for their bryophyte flora and Adélie penguin colonies[37,38]) have relatively small ice-free areas and consequently had the highest percentage of disturbed ice-free land (both ~0.067%). Although the relative footprint area may appear small, the fine scale of our dataset (smallest site = 2 m^2) surpasses the resolution of any continent-wide habitat or biodiversity mapping. Therefore, local areas of footprint may disproportionately affect significant sites within a bioregion (for example, Casey Station is situated within some of the most well-developed and extensive vegetation in continental Antarctica[10,38]). The layering of our data with high-resolution habitat datasets, as they become available, will enable further analyses.

Our dataset is the most comprehensive inventory of infrastructure across Antarctica and establishes a baseline, contributing to the Madrid Protocol's recognized need for regular and effective monitoring of environmental impacts by Antarctic Treaty countries. To date, physical footprint data[8] beyond analyses based on point locations[39], were only available for a few stations[6,40,41], despite multiple calls for continent-wide measurements[40,42,43]. The availability of this dataset will also benefit efforts to map the global 'human footprint'[39,44]. As higher-resolution imagery and data from ground truthing become available, our estimates will be refined.

A primary goal of the Madrid Protocol is the protection of Antarctic values within a systematic geographical framework. This has yet to be achieved, with only ~1.5% of ice-free areas formally designated as Antarctic Specially Protected Areas (ASPAs)[20]. Our data, coupled with increasing information about the spatial distribution of environmental values and other threats[3,45], can be used to inform and rectify this situation[6]. For example, within the Marie Byrd Land bioregion, 16,200 m^2 of terrestrial disturbance was detected but there are no ASPAs; similarly, within the Northeast Antarctic Peninsula, the area of disturbance was nearly twice the size of the protected area. While the current ASPA coverage is already recognized as not providing equal representation in all bioregions[4,6,20], the uneven distribution of disturbance identified by this study will further help inform future protected area designations.

With the tension between increasing pressure for access to the continent[12] and an international commitment to protect the Antarctic environment, cognizance of the current state of our footprint on Antarctica is essential for achieving a sustainable balance of the two. Here, our analysis can be used to inform and objectively assess strategies employed by Antarctic national programmes and tourism operators to achieve this goal. Such strategies include: identifying and setting limits on station areas to prevent disturbance-creep into intact natural environments; using existing ice-free disturbed areas more efficiently (for example, rationalization and in-filling); aiming for low disturbance to building ratios; focusing operations in more resilient environments[19]; locating new facilities on ice-covered land; and ongoing monitoring and reporting. These strategies may be particularly useful at sites where multiple parties are active; here, our data can play an important role in the further designation and management of Antarctic Specially Managed Areas. Parties may also use these data to identify areas for focused restoration efforts of disturbed sites to reduce their current footprint and support effective environmental impact assessment; in particular, understanding the environmental reference state in the location(s) of proposed activities. Finally, as scientific cooperation for projects is often fundamental and demonstrably successful in Antarctica, our findings should provide a useful incentive for better cooperation to allow international sharing of existing facilities and a higher level of importance for environmental impacts when planning new facilities, substantially assisting in the reduction of future footprint expansion.

Methods

Ice-free areas. Ice-free areas of Antarctica were determined within a GIS (ArcMap 10.3) using established 'rock outcrop' datasets from the Antarctic Digital Database (ADD). In the footprint assessment conducted for this project, omissions of ice-free areas around research stations and ASPAs that affected our analysis were identified from both recent maps: the high-resolution rock outcrop (Scientific Committee on Antarctic Research (SCAR) ADD, https://www.add.scar.org/; downloaded 1 December 2017) and high-resolution rock outcrop from Landsat 8 (https://doi.org/10.5285/f7947381-6fd7-466f-8894-25d3262cbcf5; downloaded 1 December 2017). Differences between the maps were confirmed by comparing satellite imagery against the datasets' polygons. One example of this is provided by the 5.2 km^2 entirely ice-free Yukidori Valley (APSA 141). The SCAR ADD dataset correctly classified 75% of the ice-free area, compared with just 0.5% by the Landsat 8 dataset. Due to the inconsistencies between the two rock outcrop versions, the two datasets were merged by running the 'Union' function with the two layers within ArcMap. This was found to accurately capture ice-free areas more consistently, with total area of 54,274 km^2, and 6,864 km^2 within 5 km of a coastline-only version of the ADD Medium Resolution Coastline dataset. Percentages were calculated using a total land area for the Antarctic continent of 12,188,650 km^2 (SCAR ADD, http://www.add.scar.org). While our estimate of ice-free areas may be conservative by being larger than existing estimates (44,900 and 21,745 km^2)[21], it ensured more accurate representation within our fine-scale analyses.

Footprint assessment. The locations of all known buildings and sites of terrestrial disturbance in Antarctica were compiled from maintained lists including:

- Council of Managers of National Antarctic Programs (COMNAP) Antarctic Facilities Lists for 2014, 2016 and 2017 (https://www.comnap.aq/Members/SiteAssets/SitePages/Home/COMNAP%20Antarctic%20Facilities%20List%2031%20March%202017.xlsx)
- International Association of Antarctica Tour Operators Peninsula tourism landing sites (https://iaato.org/documents/10157/323623/Antarctic+Peninsula+Sites.pdf)
- Antarctic Observing Network/World Meteorological Organization automated weather stations (https://www.ats.aq/documents/ATCM40/ip/ATCM40_ip117_e.doc)
- National Geospatial-Intelligence Agency lighthouses (https://msi.nga.mil/MSISiteContent/StaticFiles/NAV_PUBS/…/Pub111/Pub111bk.pdf)
- Antarctic Treaty historic sites and monuments (www.ats.aq/documents/recatt/att580_e.pdf)
- Aircraft landing sites (https://www.usap.gov/USAPgov/sciencesupport/GIS/documents/USAP_grundberg_fixedwing_v7.pdf; https://www.phys.hawaii.edu/elog/anita_notes/090805_112626/Field_Sites_08-09.pdf; https://www.usap.gov/USAPgov/sciencesupport/GIS/documents/FixedWingLandingFacilitesMap_2010-11.pdf)

This compilation was followed by a review of current national programme websites to search for further information on field huts, refuges and camps, as well as a search of the historical literature (for example, ref. [46]) for disused and abandoned stations.

Two main datasets were created: one containing the disturbance footprint, defined as 'visually detectable substrate disturbance within ice-free environments caused by compaction, clearing, earthworks and other landscape modification from human activities'; and one for the building footprint, defined as 'the spatial area covered by built features'[8]. We found rectified nadir imagery with a resolution sufficient to identify and map buildings and/or disturbances at 104 national Antarctic facilities listed past and present with the COMNAP[23] and a further 54 locations of huts, camps, historic sites and monuments, abandoned sites and lighthouses identified during our review. Footprint datasets were achieved by using aerial imagery as a base map, and manually digitizing discernable features into vector files in ArcMap (Supplementary Fig. 3). Sites that were discovered during the review but could not be digitized because of insufficient satellite resolution (for example, Druzhnaya-4), because they were too small to see (for example, automated weather stations), because they were buried in snow (for example, Siple Station) or because they been removed (for example, World Park Base) were recorded as additional point layers in the dataset (Supplementary Fig. 4). The mapping was done using a Lambert azimuthal equal-area projection centred on the South Pole, with the digitized files saved unprojected, based on a World Geodetic System 84 horizontal datum.

The majority (93.5%) of the base maps used were accessed through Google Earth using primarily Digital Globe images, then National Centre for Space Studies/Airbus, National Centre for Space Studies/Astrium and Landsat/Copernicus. The remaining base map sources included National Snow and Ice Data Center Operation Icebridge images and national programme mapping. When images from multiple dates were available, a preference was applied to using the most recent image, followed by the highest resolution image, and then the one with the least snow cover present. All images used were captured between October 2005 and December 2016. In nine instances, imagery from two dates was used, as snow cover obscured disturbance on more recent or higher-resolution images. All Google Earth base map images were extracted and automatically rectified using Elshayal Smart GIS software before being introduced to ArcMap. To obtain maximum resolution, aerial images were captured at an equivalent eye elevation between 100 and 343 metres. Overlapping mosaics of multiple images were used to cover larger stations that extended beyond the extent captured at this altitude (for example, Supplementary Fig. 5).

The building footprint dataset was created by manually digitizing the area of features on ice and ice-free areas (see Supplementary Fig. 3). These included stations built on ice caps and ice shelves. As this layer mapped all discernable 'built' environments, it is expected to have included temporary items such as shipping containers, equipment storage and tents, and potentially, large vehicles such as trucks and buses. Vehicles that were obvious were not included, with the exception of aircraft wreckage. The resulting digitized layer was saved into a File Geodatabase Feature Class with 5,359 individual polygons mapped.

The footprint of terrestrial disturbance was digitized using the same approach as was used by Brooks[24] (see Supplementary Fig. 3). Only disturbance visible from the imagery was mapped within ice-free areas south of 60° S. These included natural surfaces that appeared to be disturbed and compacted to a similar extent to gravel roads and other levelled areas, paved areas and areas of earthworks including where spoil from road clearing is deposited. Without ground truthing, we predict that this method detected the heaviest levels of substrate modification, with substantially more lighter levels of disturbance actually present (see the section 'Sources of error'). We also conservatively excluded features that were not visible, such as sections of road obscured by snow cover. However, terrestrial disturbance was assumed directly under building footprints in all ice-free areas. This assumption is based on the need for a building's foundations, the effects created by light obstruction, wind channelling and snow drifts. The resultant digitized layer was saved into a File Geodatabase Feature Class with 767 individual polygons mapped. Disturbance and building footprint data associated with this project are stored at https://doi.org/10.4225/15/5ae7af0fb9fcf.

Sources of error. Within our dataset, digitizing errors were expected to introduce the most error in the results. To check for error, the estimated building footprint layer for five stations was compared with known building sizes held by the Australian Antarctic Data Centre (http://data.aad.gov.au/aadc/portal/drill_down.cfm?gid=1). Of the 66 buildings cross-referenced, the new dataset had a mean area error of +2%, a mean measurement difference of +13.7 m^2 (median: +3 m^2; range: −93 to +572 m^2). As this project measured all visible built features across station environments (including fuel storage, pipes and temporary structures), the total building footprint area provided could exceed some 'permanent building' or 'under roof' measurements published elsewhere. Furthermore, the measurements provided represent what was present on the date of the imagery, and buildings may have been built/removed, or disturbance created/rehabilitated, since.

A systematic validation of our disturbance estimates against on-ground measurements was not possible, due to the scale of our analyses and the fact that no on-ground measurements exist for the vast majority of the locations. In general, we expect that our disturbance values are underestimates, because of the limitations of the available image resolution and obscured ground surfaces (for example, snow cover). As an anecdotal example, the long-term ecological monitoring project at McMurdo Station[35] measured on-ground disturbance at 2.5 km^2, whereas our estimate was 1.16 km^2. This is consistent with previous findings[24] that also demonstrated an underestimation of disturbance from aerial imagery following ground truthing. Here, many features that may be obvious on the ground, such as walking tracks, were generally below the limit of detection with our methods. While we also conducted an in-depth review of remote locations (away from stations), some sites may have been overlooked.

As was found in other studies using Google Earth images in research (for example, ref. [47]), error in the planimetric accuracy (the correct longitudinal and latitudinal placement of a feature on the Earth's surface) was expected to be small (<5 m). Because this study was focused on land areas, minor location inaccuracies were considered to be inconsequential. It is acknowledged that image resolution, rectification, projection, distortion and different image sources have the potential to introduce error. Additionally, some facilities (and disturbances) were known to be buried in ice/snow, preventing their accurate detection. The outcome of these errors, combined with the cross-referencing results, suggests that the disturbance footprint estimates presented here are probably conservative.

Statistical analysis. All area estimates were calculated using ArcMap, based on using the digitized polygons and the Lambert azimuthal equal-area projection centred on the South Pole. To provide the visual footprint results, we applied visibility distances modelled by Summerson[22] to the infrastructure mapped by this project. This involved applying buffers within a GIS to points of buildings of 20 km for stations, 10 km for abandoned stations and field camps, and 5 km for refuges, field huts, automatic weather stations, historic sites and monuments. These buffer areas were then merged, dissolved to avoid overlapping measurements, and clipped to the ADD Antarctic medium-resolution coastline to provide onshore and offshore measurements. This model was based on planar distances, with acknowledgement that local topography may decrease (or increase) the distance specific infrastructure is visible from, especially in sloping coastal areas where the majority of stations are located. To consider such error, we also ran the modelling with more conservative buffers (10 km for stations, 5 km for abandoned stations and field camps, 2.5 km for refuges and field huts, and 1 km for automatic weather stations, historic sites and monuments). The results are provided in the caption for Fig. 2. Although more sophisticated visibility modelling incorporating topography is a step closer with the Reference Elevation Model of Antarctica now providing a high-resolution digital elevation model, the height of all infrastructure above ground level would need to be established to enable such analyses.

Large contiguous ice-free areas were identified by creating a layer aggregating rock outcrop polygons (ADD high-resolution rock outcrop) that were within a maximum distance of 1 km from each other. This layer was then clipped to areas within 5 km of a coastline-only version of the ADD Antarctic medium-resolution coastline. Results were obtained by running queries against the presence or absence of a disturbance footprint within these layers.

Disturbance to building footprint ratios were calculated by dividing the disturbance area measured against the building area for COMNAP-listed locations within ice-free environments. These analyses required some exclusion of outlying data. The ratios provided for the continent included runways ($n = 68$) but excluded stations where no disturbance was detected beyond the building footprint ($n = 13$). These exclusions were sites of low intensity use (for example, field huts), stations with buildings situated on and off ice, and areas where the image resolution was insufficient to determine substrate disturbance. For the mean soil/gravel and rock outcrops ratios, runways were excluded as they create disproportionately large amounts of disturbance, with few buildings, producing high ratios that do not provide useful information in the context of the environmental management of a station area. One other outlier on King George Island was removed as it was a very small station (building footprint = 66 m^2), with a road network possibly attributed to nearby stations, creating an unrepresentative ratio. For the ratio-trend analysis of 1,000–10,000 m^2 stations, we chose to exclude McMurdo because it is over eight times larger than the next-largest station, and its relationship of buildings to disturbance did not fit the general trend of the remaining locations. Station configuration (centralized versus decentralized) was determined by assessing each location against a set of criteria. Here, centralized stations were classified as being concentrated around a single location, with similar distances between structures, and they had minimal road networks extending beyond buildings. Decentralized stations had non-concentrated layouts (often linear, or with several arms extending out), their buildings were dispersed, the roadways extended beyond the station area (often to remote buildings) and/or there were separate runways. Station substrates (soil/gravel or rock outcrop) were determined by reviewing satellite images of the stations, descriptions within the literature and Treaty documents, and eliciting expert advice from Treaty-inspection personnel.

To investigate whether disturbances to building ratios were affected by substrate (soil/gravel sites or rock outcrops), station building footprint or station configuration (centralized or not), we fitted generalized linear models with negative-binomial distributions using the mgcv package[48] in R 3.5.1 (ref. [49]). We assumed that substrate and station size effects might vary with station configuration, so we examined a set of models that included all combinations of the three variables as main effects, along with all combinations involving configuration as an interaction term. Models were compared using Akaike's information criterion (AIC)[50]. Four model structures yielded similar AIC scores that were better than all other models (Supplementary Table 3). We considered these four models to be equally plausible (the difference in AIC scores was less than 2)[50] and based our interpretation and discussion on all four. The fits of these four models to the data are shown in Supplementary Fig. 2.

Additional data sources in figures. Figs. 1 and 2 and Supplementary Figs. 1 and 4 are projected in the World Geodetic System 84 Antarctic Polar Stereographic, centred on the geographic South Pole. This uses ADD coastlines and rock outcrop layers, as detailed in the section 'Ice-free areas' (http://www.add.scar.org). The maps were produced by S.T.B. in November 2018.

Data availability

The data associated with this manuscript are stored and accessible at the Australian Antarctic Data Centre (https://doi.org/10.4225/15/5ae7af0fb9fcf). A summarized excerpt of the GIS data is also available in Supplementary Table 1.

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Author contributions
S.T.B. and D.M.B. initiated the research. S.T.B. led the development, GIS mapping and analysis, and writing of the manuscript. All authors contributed to further conceptual and content development, interpretation of the data and drafting of the manuscript.

Competing interests
The authors declare no competing interests.

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Chapter 4:

Our Footprint on Antarctica - Dataset

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Published in: Australian Antarctic Data Centre – CAASM *Metadata*

https://data.aad.gov.au/metadata/records/AAS_5134_Antarctic_Disturbance_Footprint

Created: 27th April 2018

Abstract: Knowledge of the spatial distribution and extent of infrastructure and human presence across Antarctica is critical for effectively conserving the terrestrial environment. This is particularly important for the ice-free areas. Previously, collation of such information has been prevented by inconsistent data availability from each nation in Antarctica. To address this issue, and long-standing calls to assemble this information, this project used a consistent methodology to create a new continent-wide GIS dataset. These high-resolution data captured the spatial extent of most buildings and disturbed ice-free ground and provides further vector points and lines where polygon measurements were not possible. These include: 5,455 buildings polygons, 772 disturbed ground polygons, 6 maintained traverse routes lines, 224 automatic weather station points, 58 camp points, 12 former station/hut site points, 86 Historic Site and Monument points, 280 landing site points, 18 flight route lines, 9 lighthouse points, and a further 18 station points where imagery was insufficient. Within the dataset, attributes provided include: infrastructure names, building names, substrate (ice/ice-free), and operational status. The resolution and content of this dataset enable substantial further analyses at regional and continent-wide scales, informing policy and science, and is suitable for ongoing maintenance and updates as infrastructure in Antarctica changes.

For technical approach and sources of error; see methods section of: Brooks, S. T., Jabour, J., van den Hoff, J. and Bergstrom, D. M. Our footprint on Antarctica competes with nature for rare ice-free land. *Nature Sustainability*, doi:10.1038/s41893-019-0237-y (2019).

Chapter 5:

Insights on the environmental impacts associated with visible disturbance of ice-free ground in Antarctica

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Insights on the environmental impacts associated with visible disturbance of ice-free ground in Antarctica

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Abstract: The small ice-free areas of Antarctica provide an essential habitat for most evident terrestrial biodiversity, as well as being disproportionately targeted by human activity. Visual detection of disturbance within these environments has become a useful tool for measuring areas affected by human impact, but questions remain as to what environmental consequences such disturbance actually has. To answer such questions, several factors must be considered, including the climate and biotic and abiotic characteristics. Although a body of research has established the consequences of disturbance at given locations, this paper was conceived in order to assess whether their findings could be generalized as a statement across the Antarctic continent. From a review of 31 studies within the Maritime Antarctic, Continental Antarctic and McMurdo Dry Valleys regions, we found that 83% confirmed impacts in areas of visible disturbance. Disturbance was found to modify the physical environment, consequently reducing habitat suitability as well as directly damaging biota. Visible disturbance was also associated with hydrocarbon and heavy metal contamination and non-native species establishment, reflecting the pressures from human activity in these sites. The results add significance to existing footprint measurements based on visual analysis, should aid on-the-ground appreciation of probable impacts in sites of disturbance and benefit environmental assessment processes.

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Key words: contamination, footprint, habitat, non-native species, soil, wilderness

Introduction

The extent of the human disturbance footprint for the entire Antarctic continent has recently been calculated (Brooks *et al.* 2019). This and many similar footprint studies (e.g. Kennicutt II *et al.* 2010, O'Neill *et al.* 2013) have based their assessments of disturbance on visual detection through field, aerial or satellite observations. Visible disturbance to ice-free ground has an inherent impact on the wilderness and aesthetic values of Antarctica, protected through its designation as a natural reserve by the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) (Antarctic Treaty Secretariat 1991). However, can visible disturbance also generally be associated with further impacts on physical and ecological processes across the continent? This work examines the next sequential step to these footprint measurements, as we approach this question in two ways. The first is a review of the current understanding of the origins, processes and impacts of ground disturbance in Antarctica. The second is a quasi-meta-analysis, in which we assess whether the existing literature investigating impacts in sites of disturbance is sufficient to be generalized across the ice-free areas of Antarctica, divided into three major regions: the Maritime Antarctic, Continental Antarctic and the McMurdo Dry Valleys (see the 'Regionalization' section for a more detailed explanation). In addressing this question, we also deliver a mechanistic model of disturbance processes that lead to impacts (Fig. 1), which can be applied across Antarctica.

General characteristics of Antarctic soils

In many parts of Antarctica, where polar desert soil moisture regimes occur (e.g. Continental Antarctica and McMurdo Dry Valleys), physical weathering processes dominate and chemical weathering is restricted due to cold temperatures and a lack of liquid moisture (Convey *et al.* 2014). In these dry environments, soils typically have a desert pavement surface that is composed of gravels and stones. Desert pavement forms as finer

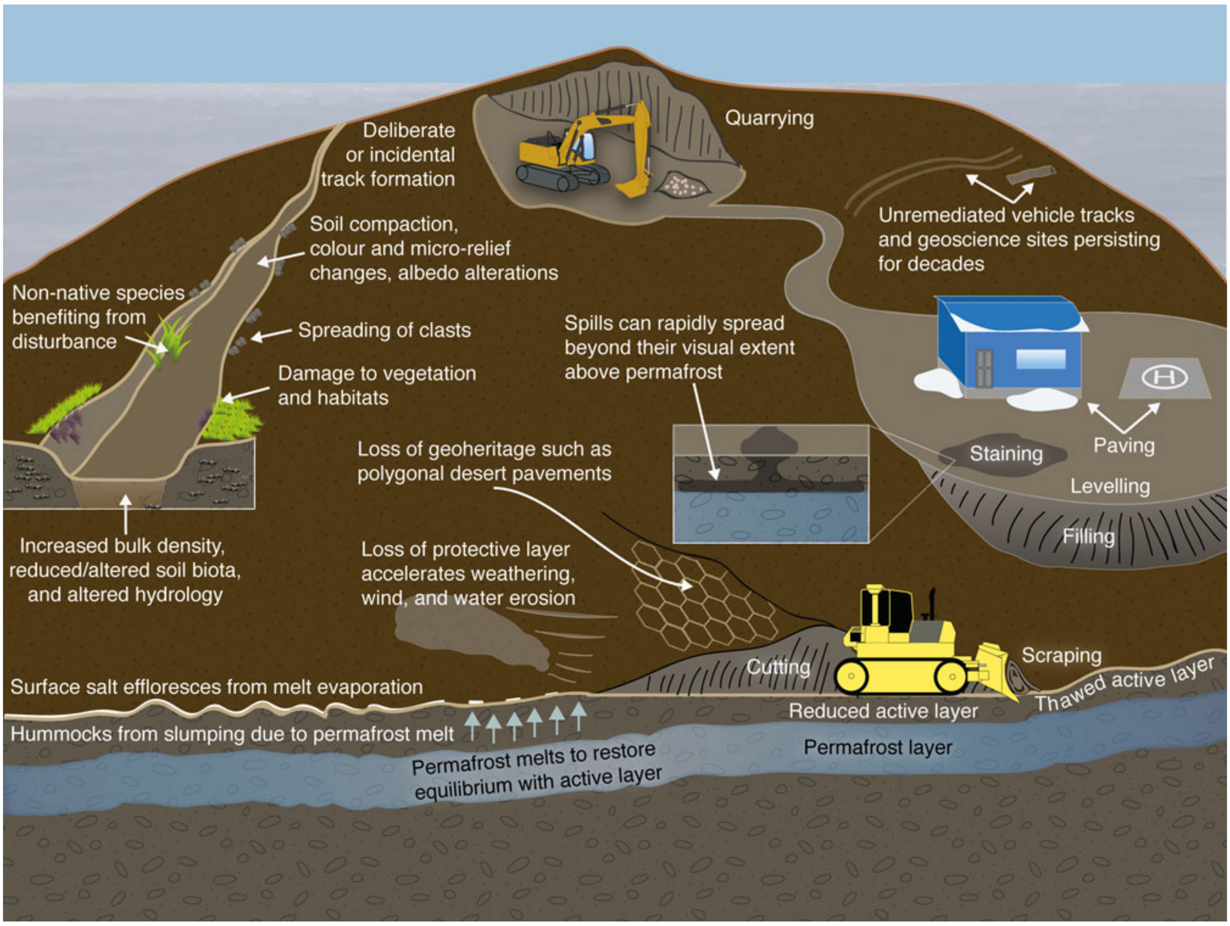

Fig. 1. Processes, impacts and visual cues associated with disturbance. This model illustrates the main processes and impacts of disturbance from human activity typically found within ice-free areas of Antarctica. Many impacts associated with track formation (top left) are also common at sites of levelling and paving (mid-right). Although infrastructure establishment to support research stations has been the biggest source of ground disturbance, pressure from walking tracks will increase as the tourism industry grows.

materials are eroded, primarily by wind, until a protective surface layer of coarser material remains. Mature, undisturbed Antarctic desert pavements are typically characterized by a closely packed layer of gravel, cobble and boulder-sized material, which can be ventifacted, pitted and coated with desert varnish, depending on age (Balks & O'Neill 2016). Beneath the desert pavement, soil materials are generally loose and unconsolidated. The depth to which soils thaw each summer is referred to as the active layer. Beneath the active layer is permafrost, defined as having a temperature of < 0°C for at least two consecutive years (Grosse *et al.* 2011, Soil Survey Staff 2014). The water content of permafrost in Antarctica can vary from being ice-cemented to dry frozen (Campbell *et al.* 1998). For much of the year, Antarctic soils are at temperatures < 0°C; however, over the summer months (December–January), when sunlight is present for up to 24 hours per day, the soils are warmed at the surface, providing some opportunity for liquid moisture and biological activity (Convey *et al.* 2018). This effect increases with decreasing latitude, being most evident within the Maritime Antarctic and a few coastal locations, where warmer temperatures and moisture availability enable sufficient biological activity to create some organic soils (Convey *et al.* 2014 and references therein). These characteristics of Antarctic soils, combined with the general absence of higher vegetation (vascular plant species) and prevailing low temperatures, result in a general vulnerability to rapid and/or long-lasting visible ground disturbance.

Significance of ice-free ground disturbance

The Antarctic continent has a land area that is larger than Europe mainly covered by ice up to 4 km thick. Despite the abundance of ice-covered environments, the majority

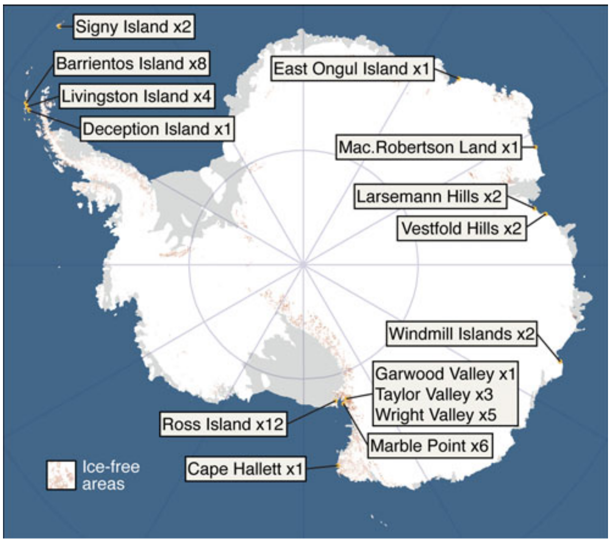

Fig. 2. Locations involved within this review. The locations involved within this review were distributed across the three broad regions of Antarctica, with concentrations in areas of accessibility, scientific interest and higher levels of footprint (see Brooks *et al.* 2019). This figure presents the locations of studies that provided specific sites. Note: several studies included sites within multiple locations.

of terrestrial biodiversity is found within the small, ice-free areas that make up < 0.5% of the continent (Convey *et al.* 2014, Brooks *et al.* 2019), centred around the Transantarctic Mountains, Mac. Robertson Land, Dronning Maud Land and the coast and islands of the Antarctic Peninsula (Bockheim 2015) (Fig. 2). These scattered 'oases' of land provide the essential habitat for Antarctica's bryophytes, lichens, microbiota, nesting seabirds, most penguin species' rookeries and two vascular plant species (restricted to the Maritime Antarctic, north of 70°S; Bergstrom *et al.* 2006; Convey *et al.* 2011, 2014). Representation of this biodiversity is not homogenous, with 16 unique areas classified by the Antarctic Conservation Biogeographic Regions (ACBRs; Terauds & Lee 2016). These areas also provide the only locations to observe Antarctic geomorphology, including rare minerals, desert pavements and finite fossil sites (Kiernan & McConnell 2001a, O'Neill 2017). Despite the outstanding scientific, environmental and ecosystem values present within these small areas, they are disproportionately impacted by human activity. The majority of all buildings on the continent (76%) are focused within just 0.06% of Antarctica, the important ice-free areas adjacent to the coast (Convey *et al.* 2014, Brooks *et al.* 2019). Accompanying these buildings are over 5.2 million m^2 of visibly disturbed ice-free ground (detectable within satellite imagery), primarily concentrated in two centres of activity (the Northwest Antarctic Peninsula and South Victoria Land), but also spread out, with more than half of all large coastal ice-free areas having impacts present (Brooks *et al.* 2019).

Sources of disturbance

Most disturbance to ice-free ground in Antarctica is in close proximity to research stations or as a result of research activities (O'Neill *et al.* 2015a, Brooks *et al.* 2019). Many of these sites have a long-term human presence, are the only permanent infrastructure on land and the human activity from their combined populations and time spent ashore far exceeds tourism (despite peaking at < 5000 people) (Jabour 2009, www.comnap.aq/Information/SiteAssets/SitePages/Home/Antarctic_Facilities_List_27July16.pdf). The disturbance footprint created by stations is a product of planned activities (permitted through environmental impact assessments), cumulative impacts and historic practices, with most disturbance having been established before the introduction of the environmental framework established by the Madrid Protocol (Brooks *et al.* 2018a, 2018b). Planned earthwork activities to establish or expand a station and its infrastructure (including roads, wharfs, airfields and fuel handling) have undoubtedly been the largest single source of ground disturbance (see Klein *et al.* 2004, O'Neill *et al.* 2015a). Scientific investigations have resulted in impacts of a similar severity, but are far less common (e.g. Kiernan & McConnell 2001a). Vehicles and to a lesser extent pedestrian activity (including substantial tourism landings) have then contributed to forming and cumulatively expanding the distribution of disturbed sites across the continent (O'Neill *et al.* 2015b).

Processes creating disturbance

The broad processes that have led to visible disturbance of ice-free areas involve adding, compacting or removing surface substrate. Adding 'fill' to areas is a common practice deliberately used to establish building foundations and road bases (Fig. 1) and has occurred in all but the most rudimentary of stations. Surrounding these areas, and at sites of scientific or tourism interest (except rocky outcrops), incidental compression and compaction of substrates occur from vehicle and pedestrian activity (including camping, helicopter landings, hut access and recreation; Tejedo *et al.* 2005, 2009). Pedestrian activity causes further disturbance through incidental spreading of clasts, degradation of surface vegetation and ecosystems and human-induced erosion (Burgess *et al.* 1992, Campbell *et al.* 1993, Pertierra *et al.* 2013, O'Neill *et al.* 2015a, 2015b). Secondary substrate compression also occurs around station facilities as a result of temporary vehicular and pedestrian access during construction activities (Brooks 2014). These processes are further intensified by most human activity in Antarctica occurring during summer, when peak active-layer melt and minimal snow cover increase the susceptibility of substrates to disturbance (Hodgson *et al.* 2010, O'Neill *et al.* 2015a, Convey *et al.* 2018). The persistence of the effects from compression depend on substrate vulnerability (O'Neill *et al.* 2015a and references therein), but have been known to result in long-lasting visual impacts as rapidly as only one pedestrian pass (Campbell *et al.* 1993, Hodgson *et al.* 2010, O'Neill 2013). Severe removal of substrates (soil/gravel and rock outcrops) is typically deliberate, in the form of quarrying, excavation and surface scraping for fill by heavy machinery (Kiernan & McConnell 2001a, Klein *et al.* 2004, Braun *et al.* 2012, 2014) (Fig. 1).

Visibility of disturbance

As a consequence of these processes and the typically vulnerable physical properties of Antarctic soils (O'Neill *et al.* 2015a), even low levels of human disturbance to ice-free ground can rapidly become visible. Due to this, visual cues are commonly used to establish and detect the severity of human impacts (e.g. Campbell *et al.* 1993, Kiernan & McConnell 2001a, Goldsworthy *et al.* 2003). Campbell *et al.* (1993) established a human impact assessment tool based on visual criteria, including surface colour changes, upturning of clasts, surface uniformity, presence of foreign objects and vegetation disturbance. Although based on the Ross Sea region, these cues have also been adapted to the Vestfold Hills (Kiernan & McConnell 2001b) and are generally applicable to the non-vegetated environments of the Maritime Antarctic. Because of this ease of detection, mapping of visibly disturbed ground has become a useful proxy for spatially quantifying sites of human impacts in the field and through remote sensing (e.g. O'Neill *et al.* 2013, Bollard-Breen *et al.* 2014, Brooks *et al.* 2019).

Impacts associated with disturbance

Disturbance to ice-free substrates throughout Antarctica generally has pronounced impacts due to the typically vulnerable physical properties of the soils, low temperatures, slow recovery rates, simple ecosystems and limited previous human activity (O'Neill *et al.* 2015a and references therein). The consequences of physical disturbance include changes to soil dynamics (moisture balance, hydrology, infiltration capacity, resistance to compression, bulk density and CO_2 fluxes), loss of the protective desert pavement surface layer (potentially resulting in landscape instability, accelerated weathering, wind and water erosion, loss of geoheritage and increased ultraviolet (UV) penetration) and melt of permafrost (O'Neill *et al.* 2015a and references therein) (Fig. 1). As permafrost can have an ice content > 80% by volume, the loss of this mass from melt (up to 250 l m^{-3}) due to removal of the insulating active layer can result in significant landscape slumping (Campbell *et al.* 1994). When permafrost melts and water evaporates, concentrated salt previously trapped in the ice-cemented layer effloresces at the surface, which can appear similar to snow (Campbell *et al.* 1994, O'Neill *et al.* 2015a). Such changes to abiotic soil conditions can be considered as environmental impacts significant in themselves and they can have flow-on effects (e.g. salt effloresces reduce surface albedo), but they can also interfere with ecosystem processes, including reducing habitat suitability (O'Neill *et al.* 2015a and references therein).

Ground disturbance in Antarctica can impact biota both directly and as a consequence of changes to their physical environment. Although edaphic species have survived for millennia in Antarctic conditions, their simplified ecosystems and adaptation to an adverse climate have generally resulted in their being vulnerable to environmental change (Convey 2010 and references therein). Loss of landscape stability, soil compression, moisture changes and a greater UV exposure following disturbance will generally reduce the habitat suitability for edaphic fauna (Wall & Virginia 1999). These may be accompanied by other environmental changes, such as soil chemistry (e.g. salinity, pH, hydrocarbons and heavy metals; Tin *et al.* 2009 and references therein) and temperature (albedo; Balks *et al.* 2002). Aboveground physical consequences to biota also occur, with cryptogamic communities being easily damaged by trampling (Pertierra *et al.* 2013), subsequently reducing the habitat and protective cover they provide (Tejedo *et al.* 2016) and further contributing to long-lasting visible disturbance (e.g. Pertierra *et al.* 2017). Physical modification of geomorphology can also have indirect impacts, with examples including Adélie penguins failing to reoccupy abandoned sites due to the past levelling of nesting mounds (Wilson *et al.* 1990). Disturbance has also been found to benefit the establishment of non-native species, especially ruderals, including the grass *Poa annua* (Molina-Montenegro *et al.* 2014). Here, disturbance and climate change (projected to also benefit non-native species; Duffy *et al.* 2017) may act synergistically, especially within the at-risk Maritime Antarctic (Chown *et al.* 2012), to increase landscape susceptibility to invasion.

Factors influencing persistence of disturbance

Although the spatial extent and severity of disturbance are dependent on the type of activity, local environmental factors and soil substrate characteristics influence the intensity and persistence of the visual impact (Brooks *et al.* 2018a). For soil and gravel environments, where 78% of stations in ice-free areas are found (Brooks *et al.* 2019), numerous factors affect recovery time. Disturbance to active environments (where wind, flowing water, waves or freeze-thaw processes are ongoing) can appear rapidly, but also disappear relatively quickly (e.g. footprints in sand dunes; O'Neill *et al.* 2015a and references therein). Beyond active environments, soil resilience in Antarctica is influenced by substrate type (including hardness, age and grain size), stage of weathering and moisture regime (O'Neill *et al.* 2015a). Older, drier, weathered sites are typically the most vulnerable, with vehicle tracks and hydrocarbon staining remaining clearly visible after 40 years (O'Neill *et al.* 2015a) and full natural recovery possibly taking hundreds of years, if it occurs at all (Kiernan & McConnell 2001b, Kennicutt II *et al.* 2010). Rock outcrop areas are inherently more resilient to human activity, apart from discolouration and damage to resident flora/lichens; however, quarrying, blasting or drilling in these environments results in irrevocable damage. Although remediation can accelerate visual recovery in certain environments (O'Neill *et al.* 2012, 2013), long-term changes to underlying permafrost persist (Campbell *et al.* 1994) and uncertainty remains regarding its effectiveness for reducing subsequent biological impacts (O'Neill *et al.* 2015a).

Materials and methods

Research approach

The aim of this paper was to establish whether the existing field of research was sufficient to infer that impacts to further values (beyond wilderness and aesthetics) can generally be expected from visible disturbance to ice-free areas across Antarctica. To assess this, our approach was based on a comprehensive review of research attempting to detect anthropogenic changes to the abiotic and biotic natural environment within sites of visibly detectable, persistent, disturbed ice-free ground. The possibility of conducting a meta-analysis or systematic review was considered, but this was not possible due to the insufficient replication of similar studies across the various species, ACBRs (Terauds & Lee 2016) or environmental domains (Morgan *et al.* 2005) present in Antarctica.

Regionalization

From the initial review, it became clear that disturbance to soil terrestrial environments in certain parts of Antarctica resulted in different impacts compared to others (e.g. the Maritime Antarctic compared to the McMurdo Dry Valleys). The consequences of disturbance were found to be linked to environmental characteristics, such as soil moisture, so different impacts were expected to be detected across Antarctica. Similarly, the research effort has focused on the impacts specifically arising from these environmental characteristics and has been concentrated within locations of accessibility, historic disturbance and scientific interest. Based on these environmental and research effort divisions, the regions determined to be relevant to this study were the Maritime Antarctic (the Antarctic Peninsula and its archipelagos) and Continental Antarctic (consistent with the traditional biogeographical zones; e.g. Huiskes *et al.* 2006) and the McMurdo Dry Valleys (divided from the Continental Antarctic due to their unique characteristics). These broad regions captured the majority of human activity in ice-free areas and provided a sufficient body of research to investigate. The main ice-free areas not captured within the continental region were inland sites, predominantly Dronning Maud Land, Marie Byrd Land and the Transantarctic Mountains (Fig. 2), due to their limited human activity, human impacts research or stations (in the latter two).

Data used

Due of the limited quantity of research investigating disturbance-related impacts in Antarctica, all findings of detected changes were considered. These ranged from reduced penguin nesting to bacterial diversity, and from soil moisture content through to changes in permafrost. In cases where multiple impacts were assessed by a single study, these were divided into separate results ($n = 15$). In total, there were 46 applicable results (from 31 studies), with many of these based on numerous study locations. The results from Molina-Montenegro *et al.* (2014), for example, were based on an investigation of 25 sites. To disseminate the gathered data, the impacts were broadly categorized as biotic and abiotic, followed by subcategories including fauna types, vegetation types, non-native species, contamination and soil properties. Each study was then reviewed for whether an impact was detected, whether quantitative analyses were performed and whether it was based on an experiment or observations. The results reported here indicate the type and number of studies investigated where changes to the environment and biota were studied. Although the changes are referred to here as 'impacts', some of the actual effects on biota or environment types may be considered small or to have resulted in negligible consequences to broader ecosystems. Alternatively, a portion of the disturbance investigated may have resulted in long-term, irreversible changes to parts of the Antarctic landscape. For example, within many Antarctic station sites, particularly those

Table I. Summary of abiotic impacts within the literature assessed. References are provided in Table S1.

Impact type	Continental Antarctica	Maritime Antarctic	McMurdo Dry Valleys	*P*-value (< 0.05)	Experiment	Site	Location	Reference
Abiotic	Impact found (+ = yes, - = no)							
Permafrost changes	+			N/A		Abandoned site	Marble Point	1
	+			N/A	Yes	Station, abandoned site	Marble Point, Ross Island	2
	+			N/A		Station	Ross Island	3
	+			N/A		Field sites	Vestfold Hills	4
Increased snow melt	+			N/A		Station	Ross Island	1
Desalinization of lakes	+			N/A		Station	Larsemann Hills	5
Increased salinity			+	N/A		Abandoned site	Wright Valley	6
Soil moisture changes	+			Yes		Station	Ross Island	7
	-			Yes		Station, abandoned site	Marble Point, Ross Island	8
		+		Yes	Yes	Footpath	Livingston Island	9
		+		Yes		Footpath	Barrientos Island	10
Lowered pH			+	N/A		Abandoned site	Wright Valley	6
Soil compaction	+			Yes		Footpath	Ross Island	11
		+		Yes	Yes	Footpath	Livingston Island	12
	+			N/A		Footpath	Ross Island	13
		-		Yes		Footpath	Barrientos Island	10
		+		Yes	Yes	Footpath	Barrientos Island	14
Soil eutrophication	+			Yes		Station	East Ongul Island	15
Soil physiochemical properties	-			N/A		Footpath	Ross Island	11
		-		Yes		Footpath	Barrientos Island	10
Heavy metals contamination	+			N/A		Abandoned site	Marble Point	16
	+			N/A		Station, abandoned site	Marble Point, Ross Island	17
			-	N/A		Abandoned site	Wright Valley	17
			+	N/A		Abandoned site	Wright Valley	6
Hydrocarbon contamination	+			N/A		Station	Larsemann Hills	18
Reduced soil albedo	+			Yes		Station, abandoned site	Marble Point, Ross Island	8

built before the Madrid Protocol, disturbance of a high severity is common (O'Neill *et al.* 2015a; O'Neill 2017).

Results

Of the 46 results reviewed, 83% ($n = 38$) found further impacts in sites of disturbance (Tables I & II). Half of all studies involved used statistically robust sampling techniques, whereas the remainder reported on measurements and observations. From the half that used statistical analyses, 74% found that impacts were present ($P < 0.05$). In total, nine of the reports were based on experimental disturbance of a site to enable detection of impacts under controlled conditions (Tables I & II). Twenty-two of the reports were from Continental Antarctica (eight locations), 17 were from the Maritime Antarctic (four locations) and seven were from the McMurdo Dry Valleys region (three locations) (Fig. 2).

The majority of all reports from Continental Antarctica investigated abiotic impacts, whereas the majority of Maritime Antarctic reports studied biological values. The seven reports from the McMurdo Dry Valleys were split between abiotic and biotic impacts, reflecting both the focus and limited quantity of applicable studies there. In total, 81% of abiotic studies reported an impact ($n = 22$) and 84% of biotic studies reported an impact ($n = 16$) (Tables I and II). Changes to soil properties were the most common form of impact assessed ($n = 18$), followed by impacts to fauna ($n = 11$), contamination ($n = 6$), degradation of flora ($n = 4$) and non-native species ($n = 4$). The majority of studies investigated sites of current or former stations ($n = 24$), followed by footpaths/walking tracks ($n = 18$) and scientific field sites ($n = 3$).

Discussion

The majority of studies involved in this review identified biotic and abiotic environmental impacts (beyond wilderness and aesthetic values) within sites of lasting visible disturbance. Although the consequences of

Table II. Summary of biotic impacts within the literature assessed. References are provided in Table S1.

Impact type	Continental Antarctica	Maritime Antarctic	McMurdo Dry Valleys	*P*-value (< 0.05)	Experiment	Site	Location	Reference
	Impact found (+ = yes, - = no)							
Biotic								
Collembola		+		Yes	Yes	Footpath	Livingston Island	19
		+		N/A		Footpath	Barrientos Island	20
Nematodes			+	Yes		Footpath	Taylor Valley	21
			+	Yes	Yes	Field sites	Garwood, Taylor and Wright valleys	22
Soil biota (nematodes, rotifers and tardigrades)			+	Yes		Footpath	Taylor Valley	21
Soil bacteria		-		Yes		Station	Signy Island	23
		+		N/A		Station	Signy Island	23
		+		Yes		Footpath	Barrientos Island	10
	-			Yes		Station	Windmill Islands	24
	-			Yes	Yes	Station	Ross Island	25
Fungi	+			N/A		Field sites	Vestfold Hills, Mac. Robertson Land	26
Penguins	+			N/A		Abandoned site	Cape Hallett	27
Moss		+		N/A		Footpath	Deception Island	28
		+		Yes		Footpath	Barrientos Island	20
Moss/lichen		+		Yes	Yes	Footpath	Livingston Island	9
	+			N/A		Station	Ross Island	29
NNS - Collembola		+		N/A		Footpath	Barrientos Island	20
NNS - fungi	+			N/A		Station, abandoned site	Windmill Islands	30
NNS - grass (*Poa annua*)		+		Yes		Station	Various	31
		+		Yes	Yes	Station	Various	31

NNS = non-native species.

disturbance vary by region across the continent, as do the focuses of the studies, the majority of cases reviewed here suggest, in most circumstances, that with similar environmental conditions further impacts are probable. While this was the hypothesized result, conducting a continent-wide review has helped to establish the likelihood that such findings could be generalized as a statement across the whole Antarctic continent. Although the statistical rigour of a meta-analysis was not possible, Tables I & II have provided a summary of the current knowledge regarding the ecological and physiological consequences underlying visibly disturbed ground in Antarctica.

How impacts occurred

There were three broad, interrelated pathways identified within this review where ground disturbance led to further impacts. For biotic impacts, ground disturbance typically led to increased soil bulk density (compaction) and altered moisture availability, consequently reducing the habitat suitability for flora and edaphic fauna. This disturbance also caused direct mechanical damage of biota. This alteration of soil habitats may also benefit non-native species establishment (as with natural perturbation; Olech 1996, Olech & Chwedorzewska 2011, Molina-Montenegro *et al.* 2014). For abiotic impacts, disturbance modified the natural protective desert pavement surface layer (which may also damage unique geomorphological values), typically disturbing or removing the active layer, forcing the disturbed permafrost to re-establish an equilibrium with the surface. In many cases, melt out of permafrost led to surface slumping and surface salt efflorescence, leading to further negative biological effects. The third pathway is the virtually unavoidable concomitant pressures of human activity associated with disturbed ground. These include contamination with hydrocarbons, heavy metals, eutrophication and non-native species introductions, all of which are inherently more common in locations of long-term human presence and activity (e.g. Bargagli 2008, Cowan *et al.* 2011, Klein *et al.* 2012, Houghton *et al.* 2014, Brooks *et al.* 2018b, Newman *et al.* 2018).

The consequences of disturbance can also extend out beyond visibly impacted areas. As there are very few paved roads within Antarctica, the utilization of gravel roads can cause erosion, run-off and the generation of dust (e.g. Campbell *et al.* 1994). Although liquid water is relatively scarce in Antarctica, summer melt is known to channel in roads, leading to sedimentation and altered salinity within Antarctic lakes (Burgess *et al.* 1992). This limited moisture availability can also increase the concentration of contaminants within run-off due to the lack of regular flushing (Sheppard *et al.* 1997, Claridge *et al.* 1999). Within moister environments, where ice-cemented permafrost occurs, contaminants such as fuels can also spread rapidly underneath the surface beyond the visible spill point by migrating laterally on top of the frozen layer (Claridge *et al.* 1999, Campbell *et al.* 2003) (Fig. 1). Although dust generated from disturbed ground and deposition onto snow and ice is known to increase meltwater in Antarctica (Campbell *et al.* 1994), the edge effects and dust deposition from heavily disturbed ground (such as roads and staging areas) on surrounding flora and edaphic fauna have been observed, but such observations are currently unpublished. Within the Arctic, examples of gravel road edge effects include higher pH, reduced nutrients, increased bulk density, lower moisture content, altered snow cover, deeper permafrost thaw, reduced species richness and between two to five times less vegetation biomass at 2 m from the road compared to 100 m distance (Auerbach *et al.* 1997). While acknowledging substantial environmental differences from the Arctic, some of these effects must occur in Antarctica, and so these warrant further study where new roads are proposed in ice-free areas.

Regional differences in impacts associated with visible ground disturbance

The locations of the studies involved were typically accessible sites frequented by human activity, sites of significant past human impacts including contamination or sites of scientific interest (Fig. 2). For Continental Antarctica, nine of the 22 reports were from sites surrounding McMurdo Station and Scott Base on Ross Island, reflecting the relative accessibility, concentration of research activities and long-term human presence and subsequent landscape degradation in the area. A further six studies were based on Marble Point, typically the access point to and from the McMurdo Dry Valleys and Northern Victoria Land (across McMurdo Sound from Ross Island), which was greatly impacted by an abandoned attempt to build a 3 km runway there in the late 1950s (Broadbent 2009). Research within the McMurdo Dry Valleys was split between the former Vanda Station site and the formation of walking tracks from science and tourism. The focus of these studies was on abiotic conditions (which ultimately drive biology) and probably reflects both the long-term persistence of impacts and typically sporadic biota within these cold desert environments.

Studies from the Maritime Antarctic, however, were focused on the more pronounced biota in this region, concentrating on islands, non-native species and walking track formation. This biotic focus is consistent with the increased biological activity that occurs there, supported by the wetter moisture regime, more mature soils and warmer temperatures. The emphasis on tracks within ice-free areas may be attributed to the Maritime Antarctic representing the most diverse terrestrial Antarctic ecosystems (Convey 2010, Tejedo *et al.* 2016), more walking-based scientific activity (Pertierra *et al.* 2017) and relatively frequent pedestrian activity introduced by ship-based tourism. By extrapolating these results to station environments within the region, heavily disturbed sites with intense human activity are expected to have similar or more pronounced impacts compared with those found from walking tracks. The northern Antarctic Peninsula and South Shetland Islands are also consistently recognized as the most susceptible parts of the continent to non-native species invasion due to ease of accessibility and comparatively milder climatic conditions (Chown *et al.* 2012), warranting the research effort. As shifts in the viability of biota due to climate change are already being detected at Maritime Antarctic sites (Amesbury *et al.* 2017) and on the continent (Robinson *et al.* 2018), the impacts associated with disturbance will probably have a changing and possibly compounding effect with projected warming (e.g. Duffy *et al.* 2017, Lee *et al.* 2017).

Research gaps

Finally, we must highlight that the process of this review has helped identify gaps in the current field of knowledge. This study focused on impacts detected within the immediate proximity of visible disturbance. Many of these impacts are known to extend out beyond the obviously disturbed area (e.g. dust settling on vegetation), but there is currently limited research available from Antarctica to quantify these effects. Investigation into the effectiveness of remediation of disturbed sites in relation to the impacts reviewed here (beyond contamination, wilderness and aesthetic values) warrants further research. Furthermore, this study has highlighted significant regional differences in subsequent impacts from disturbance, and as a consequence we recommend adapting the criteria used in visual site assessment tools (e.g. Campbell *et al.* 1993, Kiernan & McConnell 2001b, O'Neill *et al.* 2012) to allow their application to the vegetated areas typical of the Maritime Antarctic. Utilization of these modified visual site assessment tools in these areas should enable practical improvements in environmental impact assessments and disturbance mitigation measures for use within Antarctica.

Conclusion

Compared with all other continents, the area of Antarctica observably modified by human activities is very small. This is consistent with its designation as a natural reserve. The current footprint of disturbance, however, takes on more significance considering its focus within the most biologically significant parts of the continent, concentrated by short influxes of human activity during the summer when substrates are most vulnerable. Many of the impacts reported here may not be considered severe, but they all affect environmental and ecosystem processes protected by the Madrid Protocol.

Our results suggest visually observable disturbed ground within the ice-free environment across Antarctica is, in most cases, an indicator of further impacts to biotic and abiotic processes. This adds a layer of significance to the 5.2 million m^2 of disturbed ground measured from satellite imagery, as well as adding value to all of the existing studies that have used visual methods to assess local-scale human impacts. These results and the summary of the literature should be of value to studies of disturbance in ice-free areas (from science and tourism activities), as well as providing a tool for observers for rapid assessment of potential environmental impacts seen during Antarctic Treaty station inspections. Similarly, this collation of data across the range of possible impacts associated with ground disturbance should help environmental management teams determine the accuracy of the probable impacts of proposed activities estimated within environmental impact assessments.

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Author contributions

STB initiated the research and prepared a first draft of the manuscript and figures. All authors contributed to conceptual development, research, further drafting and revisions of the manuscript.

Details of data deposit

All data used within our analyses were extracted from publicly available published articles listed in Table S1.

Supplementary material

One table will be found at https://doi.org/10.1017/S0954102019000440.

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Chapter 6:

Conservation Planning for Antarctic Research Stations

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Abstract

The small ice-free areas of Antarctica are essential locations for biodiversity and science, but are also subject to pronounced and expanding human impacts from research station activity. Awareness of the need to conserve these natural values by station operators does exist, but management of impacts typically occurs on a reactive basis. While there has been growing momentum to expand Antarctic Specially Protected Areas to conserve such values, there is also a need for overall management of impacts to be commensurate with the continent's designation as a natural reserve. By using a case study of Australia's Casey Station, this project found significant natural values still persist within close proximity of long-term station infrastructure, but encroachment by the footprint of activity has been an ongoing pressure. Here, strategic planning to better conserve such values provides a direct opportunity to enhance protection of the Antarctic environment. This paper introduces a systematic conservation planning approach, tailored to Antarctic research stations, to aid operators to improve the conservation of values surrounding their activities. Use of this approach provides an opportunity to balance the need for scientific access to the continent with international obligations to protect the environment.

Keywords

Footprint, values, pressures, human impacts, wilderness, environmental management.

Introduction

Antarctica is unique; as the world's least modified continent it is widely recognised for its scientific and natural values (Brooks et al., 2019; McLean & Rock, 2016). Its geographical and climatic separation, however, does not isolate it from the pressures of climate change and pollution emanating from the rest of the World (Chown et al., 2012). While tackling these pressures are global challenges, human impacts from local activity on the continent are also substantial (Brooks et al., 2019; Tin et al., 2009), and expanding (Chown, 2018; Convey et al., 2012), providing direct opportunities for improved protection of the Antarctic environment. The source of these local impacts is somewhat paradoxical though; science and tourism activities which seek Antarctica's intact environment, and the logistical support needed to access it, has been accompanied by disturbance and contamination that has subsequently degraded many locations (Brooks et al., 2019). Furthermore, there is a general absence in strategic coordination of how we manage our known impacts (Roura & Hemmings, 2011). To aid balancing this desire for access to the continent with international obligations to protect the environment, this paper provides a process for developing conservation planning for the management of the most pronounced sites of ongoing human impacts on the continent: Antarctic research stations.

Although the history of current Antarctic station sites date back to 1904, the contemporary era of research stations began in the 1950s, with year-round operation beginning at Mawson in 1954 (Brooks et al., 2019; COMNAP, 2017). Since their establishment, the key functions of stations have been to provide shelter, accommodation, communications, store supplies, house research infrastructure, and to act as logistical hubs. These functions have, however, evolved (and typically expanded) to accommodate increasingly complex research equipment, technological advances, larger populations, safety requirements, and comfort (Brooks et al., 2019; Klein et al., 2008; Nielsen, 2013). As two-thirds of current stations were established prior to 1991 when the current framework for comprehensive environmental protection was adopted by the Antarctic Treaty Consultative Parties (the Protocol on Environmental Protection to the Antarctic Treaty [Madrid Protocol])(ATS, 2019), many also have significant 'legacy' impacts from long-discontinued practices. Now, with a main exception of accidental fuel spills (Brooks et al., 2018b), the largest source of human impacts from stations are planned activities permitted through environmental impact assessments (EIA), which are following a course of continuous growth with international interest in new stations, modernisation of existing facilities, and expansion in the range of capabilities supported (Brooks et al., 2018a; Brooks et al., 2019; Chown, 2018; Convey et al., 2012; Price, 2019; United States, 2019; Willams, 2019).

An opportunity to balance this increasing footprint in Antarctica against obligations to protect the environment, agreed upon under the Madrid Protocol, can be provided through deliberate and strategic conservation planning of station sites. Recognition of the value of conservation planning for stations spans the duration of the Antarctic Treaty (Carrick, 1960), with many specific recommendations for planning, zoning, and monitoring being provided through the proceeding decades (*e.g.* Brooks, 2014; Kriwoken, 1991; Roura, 2004; Walton & Shears, 1994). Similarly, examples of valuable environmental research programs, monitoring, and remediation methodologies have been developed (*e.g.* Klein et al., 2014; O'Neill et al., 2012; Tejedo et al., 2016). To date, however, there are few published examples of consolidated, systematic, or successful conservation planning approaches to manage environmental protection for station sites.

To address this gap, I have tailored a systematic conservation planning approach, developed from consolidated international approaches (i.e. Pressey & Bottrill, 2009), for Antarctic stations and have provided an in-depth case study of its application on Australia's Casey Station. Systematic conservation planning is the process of deciding how to most efficiently use finite resources for conserving natural values within a framework which sets clear and explicit goals and considerations, prescribes how goals are addressed, acknowledges current achievement towards objectives, and provides a structure to maintain the effectiveness of conservation actions (Margules & Pressey, 2000). This approach complements broader-scale systematic conservation planning in-development for the Antarctic Peninsula region (IAATO & SCAR, 2019), and suggested use for expanding the Antarctic Specially Protected Area (ASPA) network (Coetzee et al., 2017), as well as meeting the aim of adapting international best practice conservation methods to the specific circumstances of Antarctic stations (*sensu* Hughes et al., 2018).

Focus on Ice-Free Areas

In total, less than half a percent of Antarctica remains ice-free (Brooks et al., 2019). The coastal ice-free areas (within 5km of coast), where the environmental envelope is most suitable for vegetation and accessible for wildlife, is even less again, constituting around 0.06% of the overall landmass (Bergstrom et al., 2006; Brooks et al., 2019). By considering biodiversity data and physical parameters, these ice-free areas have been further divided into 16 biologically-distinct Antarctic Conservation Biogeographic Regions (ACBRs) (Terauds et al., 2012; Terauds & Lee, 2016). These scattered 'islands in ice' are vital locations for science and biodiversity, providing key habitats for Antarctica's terrestrial wildlife, two vascular plant species, mosses, and lichens, most vertebrate breeding sites, as well as providing the most accessible locations for studying Antarctica's geoheritage (Bergstrom et al., 2006; Chown et al., 2015; Convey & Stevens, 2007; O'Neill, 2017; Pertierra & Hughes, 2019). Human activity is also disproportionately concentrated within these ice-free areas as they accommodate 81% of all station infrastructure, with 76% just in the coastal margin (Brooks et al., 2019). The human impacts to ice-free areas are also spread out, with over half of all large coastal ice-free areas having disturbance visible from satellite, present (Brooks et al., 2019). Many stations are also within sites of exceptional values such as my case study, Casey Station, being situated within an area considered vital for Antarctic biodiversity (Robinson et al., 2018). As a consequence, despite individual station sites appearing to be insignificantly small against the scale of the continent, their footprints can have profound impacts on natural values (*e.g.* Brooks et al., 2019) warranting management for conservation. Although the outputs from this project are applicable to locations across ice-covered Antarctica, the combination of focussed values and pressures from human use within ice-free areas, created by the presence of stations, form the motivating force behind the need for systematic conservation planning.

Impacts on Values

Antarctic stations create focal points of human activities that are inevitably accompanied by impacts to the environment (Bargagli, 2008; Jabour, 2009; Tin et al., 2009). The extent and intensity of impacts, however, is varied and determined by a station's size, layout, management, construction method, technology, intensity of use, and importantly, the sensitivity of the receiving environment (Brooks, 2014; Brooks et al., 2019; O'Neill, 2017). Considered in the context of values protected by the Madrid Protocol, typical impacts to terrestrial ecosystems from established stations include hydrocarbon, heavy metal, chemical, microbial, and genetic contamination (Kennicutt II et al., 2010; Klein et al., 2012; Tin et al., 2009), waste dispersal and pollution (Brooks et al., 2018b; Cincinelli et al., 2017; Fryirs et al., 2013; Reed et al., 2018), habitat displacement (Micol & Jouventin, 2001; Wilson et al., 1990), and non-native species introductions (Frenot et al., 2005; Houghton et al., 2014). At coastal sites, contamination from sewage discharge and chemical run-off further extend impacts into the marine environment (*e.g.* Snape et al., 2001; Stark et al., 2016). Such pressures also implicitly impact scientific values through modifying natural baseline ecosystems (Bergstrom et al., 2006) and landscapes (*e.g.* the construction of a runway at Mario Zuchelli Station will destroy a large portion of a long-term climate change soil monitoring site; Italy, 2016). Similarly, modifications to the environment can result in irreversible losses in unique geomorphological and geological features of scientific value (Hughes et al., 2016; Klein et al., 2004; O'Neill, 2017). Although historic values within close proximity to stations can have enhanced conservation attention due to their accessibility, they conversely create recreational drawcards resulting in ongoing visitation which impacts their archaeological significance and results in cumulative degradation (Bickersteth et al., 2008; O'Neill et al., 2013). The presence of stations, and the impacts listed above, can also degrade wilderness and aesthetic values. Although these intrinsic values can be problematic to quantify, station buildings, known to impact these values, are estimated to have a visual footprint similar in size to all ice-free areas (Brooks et al., 2019; Summerson & Bishop, 2012).

Station Footprints

Understanding the 'footprint' human impacts have on surrounding natural values is essential information for Antarctic environmental management (Brooks et al., 2018a; Walton & Shears, 1994). The footprint of a station can describe the area effected by a specific impact (*e.g.* hydrocarbon contamination of soil) (Brooks et al., 2018a), or capture impacted areas more broadly through measures such as visibly disturbed ground or areas accessed (*e.g.* Brooks et al., 2019; Pertierra et al., 2017). The use of disturbance footprint, as a proxy representative of multiple impacts, is supported by numerous studies of the physical and biological pressures which result from disturbed substrate across Antarctica's ice-free regions (Brooks et al., in press). Typically, the intensity of a station's footprint will be most concentrated in areas of focussed activity (i.e. the centre of a station) (Hull & Bergstrom, 2006), then gradually decreasing outwards towards a baseline natural state (*e.g.* Corbett et al., 2015; Khan et al., 2019). The outer limits of footprint often extend well beyond the immediate area of a station, though, through establishment of remote infrastructure such as roads (Brooks et al., 2019), walking tracks (Braun et al., 2012), and field sites (Bollard-Breen et al., 2014; Pertierra et al., 2013). How a station is planned also affects its footprint, with centralised infrastructure resulting in substantially smaller areas of disturbance (Brooks et al., 2019). While the total footprint from all human activity (including tourism) across Antarctica is relatively small, the spread of disturbance is significant (Brooks et al., 2019), warranting improved conservation planning and management commensurate with the continent's designation as a natural reserve (ATS, 2019).

Current Conservation Planning

The responsibility for environmental management, and any supporting conservation planning, of Antarctic stations lie with the national Antarctic programs (hereinafter national programs) that operate the facilities. This is based on obligations prescribed under the Madrid Protocol which are enacted through domestic legislation for each signatory Party (*e.g.* Australia, 2017). Environmental management by national programs is supported by knowledge-sharing and international policy development through fora including the Committee for Environmental Protection (CEP) and the Council of Managers of National Antarctic Programs (COMNAP), feedback from Antarctic Treaty station-inspection reports, and from expert groups including the Scientific Committee on Antarctic Research (SCAR). In a handful of cases, national programs are further supported by standardised environmental management systems such as ISO14001 (Sánchez & Njaastad, 2014). In regards to fuel handling, biosecurity, and contemporary pollution management, national programs generally demonstrate a high-level of diligence and recent measures put in place have improved the protection of the Antarctic environment (*e.g.* Brooks et al., 2018b; Chown et al., 2017; Houghton et al., 2014; Hughes et al., 2009; Newman et al., 2018).

The effectiveness of current environmental management and conservation planning for containing the growth of station footprints across the continent and their subsequent impacts on natural values, however, is less evident (*e.g.* proceeding section: *Casey Station Case Study, Pressures*) (Chown et al., 2017). There are many possible reasons attributable for this including a general lack in coordination, strategic oversight or effectiveness of EIAs to reduce impacts (Hemmings & Kriwoken, 2010; Roura & Hemmings, 2011), inadequate resourcing to implement practical controls (Sánchez & Njaastad, 2014), as well as insufficient monitoring to detect cumulative impacts and change (Hughes, 2010; O'Neill, 2017). In addition to the impacts a 'creeping' footprint can have on natural values, a general lack of boundaries to limit station expansions, both planned or incidental, has contributed to the criticism Antarctica's environmental protection doesn't adequately meet the expectations of a 'natural reserve' (Coetzee et al., 2017).

Justification for Further Conservation Planning

Although Antarctica's unique international governance makes it difficult for the continent to conform to established definitions of a protected area (Bastmeijer & van Hendel, 2009; Chown et al., 2017; IUCN, 2019), improved conservation planning to manage the most intensely impacted sites (i.e. stations) may bring it closer in line. One of the more prominent challenges for the continent to meet the definition of a protected area is the absence of limits, or management in place, to prevent activities that cause potentially significant conservation impacts (Bastmeijer & van Hendel, 2009; Coetzee et al., 2017). A reaction, partly from this, has been a concerted effort to increase the coverage of Antarctic Specially Protected Areas (ASPAs), particularly within the terrestrial environment (Australia, 2019; Chown et al., 2017; Coetzee et al., 2017; Shaw et al., 2014; Terauds & Lee, 2016). This focus has been based on the recognition the current coverage of ASPAs across Antarctica does not comprehensively protect all ecosystems and biodiversity (Wauchope et al., 2019), biogeographical regions (Terauds & Lee, 2016), or landscapes (Hughes et al., 2016). Despite awareness of inadequate representation within the network, the total land area covered by ASPAs has remained almost static for ~40 years (Chown et al., 2017). While efforts to expand the ASPA network to a representative system should be commended, and are consistent with the Madrid Protocol (Annex V, Article 3.2), the CEP asserts the need within this discussion to recognise the entire continent receives environmental protection (Australia, 2019). Here, steps should be taken to strengthen this overall protection of Antarctica in parallel with efforts promoting further ASPA coverage (Bastmeijer & van Hendel, 2009). This is where explicit conservation planning within the environmental management of a station provides an opportunity: by proactively minimising and containing the impacts a station and its related activity has on surrounding natural values, national programs can demonstrate their commitment to Antarctica's designation as a natural reserve and simultaneously work towards offsetting criticism the continent is not adequately protected.

Methods:

Developing a Systematic Conservation Planning Approach for Stations

This approach to systematic conservation planning is designed to produce a scalable-tool prescribing planning considerations for use by anyone involved in the environmental management of an Antarctic station. Its intent is to facilitate improved conservation of values within the constraint of not inhibiting the functional role a station provides. The guidance it provides may be tailored for planning any conservation goals or projects surrounding station sites, regardless of scale and complexity. Here I have used nine stages of systematic conservation planning (Table 1) primarily adopted from Pressey and Bottrill (2009) to meet the needs unique to station environments (i.e. self-sufficient logistical hubs). The process was prototyped around a case study of Australia's Casey Station and refined through consultation with national program personnel through multiple workshop environments. Within the workshops, participants from science, policy, and operational branches were presented with data gathered on values and pressures within the case study station's area (Supplementary Information 1 & 2), and asked how applicable the nine-stage-structure was for meeting their operational needs (Table 1). Their responses were then used to further develop the conservation planning stages (Table 1 and Supplementary Information 1). This consultation process revealed many

Table 1: The stages of Systematic Conservation Planning.

See Supplementary Information 1 for planning tool expanding each stage.

1. Scoping and the planning process: Determination of the geographic boundaries of the planning area is required, along with the techniques to be used to inform the process. The framework and resources (capacity) needed to implement each stage should also be identified.

2. Identifying and involving stakeholders: Stakeholders are those who operate or use Antarctic research stations. Although stations are generally national government facilities, many are operated by several different agencies, with differing needs and goals. Additionally, many are also operated by, or in concert with, research organisations, foundations, universities, contractors, and military logistical support. The process of identifying stakeholders should include determining the extent they will influence, be affected by, or have responsibility for implementing, the planning process.
Engagement with the primary operators of a station is key to successful implementation and should take place early within the process. Involvement with remaining stakeholders should be proportional to the extent they are affected by the planning.

3. Describing the context for Research Stations: Antarctic research stations are inherently varied in history, function, activities, location, and management, providing support for a range of research disciplines. This background requires consideration of the social, economic & political setting for conservation planning. Similarly, the types of threats to natural features that can be mitigated by spatial planning as well as the broad constraints on, and opportunities for, conservation actions, need identification.

4. Identifying conservation goals: Conservation goals for a station will be determined by its context (Stage 3), compliance with the Environmental Principles (Article 3) of the Protocol on Environemental Protection to the Antarctic Treaty), and the legal requirements and cultural expectations of its operator's nation. These should be broad statements which are progressively refined into qualitative goals about the preservation of values. These goals should help identify data requirements (Stage 5).

5. Values and pressures (data collection and creation): Collection and creation of information on biological, scientific, historic, aesthetic, and wilderness values present within the planning area; as well as threatening processes, with a focus on spatially explicit data. Data is collated to map constraints and opportunities for conservation actions. Will also involve predictions about the expansion of threatening processes. This process should identify gaps in information where further assessment, or the precautionary principle, should be applied.

6. Reviewing current achievement of objectives: All research station operators will have existing laws, approaches, and management in place to meet their environmental protection obligations under the Antarctic Treaty System. The effectiveness of these, along with any additional domestic measures, should be assessed against field data for their adequacy to achieve desired conservation objectives. This assessment will inform their contribution to, or potential integration within, conservation planning, as well as identify what objectives have already been achieved.

7. Setting conservation objectives: Assessing conservation goals against values and pressures data to set clear quantitative objectives. This will include spatially-explicit targets for the conservation of natural values, ongoing human pressures (e.g. current and future footprint projections), and qualitative objectives related to management strategies for degraded areas, station configurations, and other criteria.

8. Applying conservation actions to stations: Applying conservation actions to a station will require a variety of administrative, legal, operational, scientific, and technical pathways. Many components of these actions will already be in place (e.g. environmental impact assessment), but may be more effective if brought together with conservation planning. As the capacity to implement these actions will be finite, priority listing should be provided; based on an assessment of values, risk of further impact, feasibility, and appropriateness.

9. Maintaining and monitoring achievement of objectives: Management strategies are put in place to ensure conservations actions are effective, sustainable in the long-term, and contribute towards promoting the persistence of values around station activities and meeting objectives. These will require the periodic monitoring of values and pressures against baselines or targets to inform planning efficacy. Review periods should also be set to assess progress towards achieving conservation goals.

interconnected issues when addressing conservation improvements but consistently corroborated the applicability of the stages of systematic conservation planning. To aid utilisation of the stages of planning, a support tool providing steps and examples is provided (Supplementary Information 1).

Casey Station Case Study

Background

Australia's Casey Station is located within the Windmill Islands along the Budd Coast in East Antarctica (66°16′57″S, 110°31′36″E). Its original construction began in the 1960s to serve as a replacement for the now abandoned Wilkes Station (located ~2.5km north on the opposite side of Newcomb Bay), and has continued to evolve and expand southwards (peaking during the 1980s), to accommodate new buildings and infrastructure. The Windmill Islands region consists of a series of ice-free islands and peninsulas which are consistently recognised as one of the most important areas of continental Antarctica for biodiversity (Robinson et al., 2018), especially for bryophyte-dominated vegetation (Melick et al., 1994; Smith, 1988). These values are particularly prominent within the Bailey and Clark Peninsulas where Casey and Wilkes Stations respectively are located (Melick et al., 1994). The region, and especially its islands, is also known for its important bird breeding areas (Harris et al., 2015). Consequently, there is now the human activity, disturbance, and legacy impacts from 60 years of occupation, closely surrounded by exceptional values deserving conservation.

Values

Australian Antarctic Data Centre (AADC) records, scientific literature, and the SCAR Biodiversity Database were reviewed for any applicable data on values present within the immediate vicinity of Casey Station (see Supplementary Information 2). In total five bryophyte and 24 lichen species were reported, occurring with high frequency and density close to infrastructure (Figure 1 & 2). Fourteen algal species and numerous bacteria have also been found, but whether these are significant was not determined. Three flying bird species are recorded, with snow petrel nesting sites surrounding station infrastructure (Figure 1). Adélie penguins are frequent visitors to the station area with the nearest rookery located ~750 metres west on Shirley Island. There are no important seal sites within the

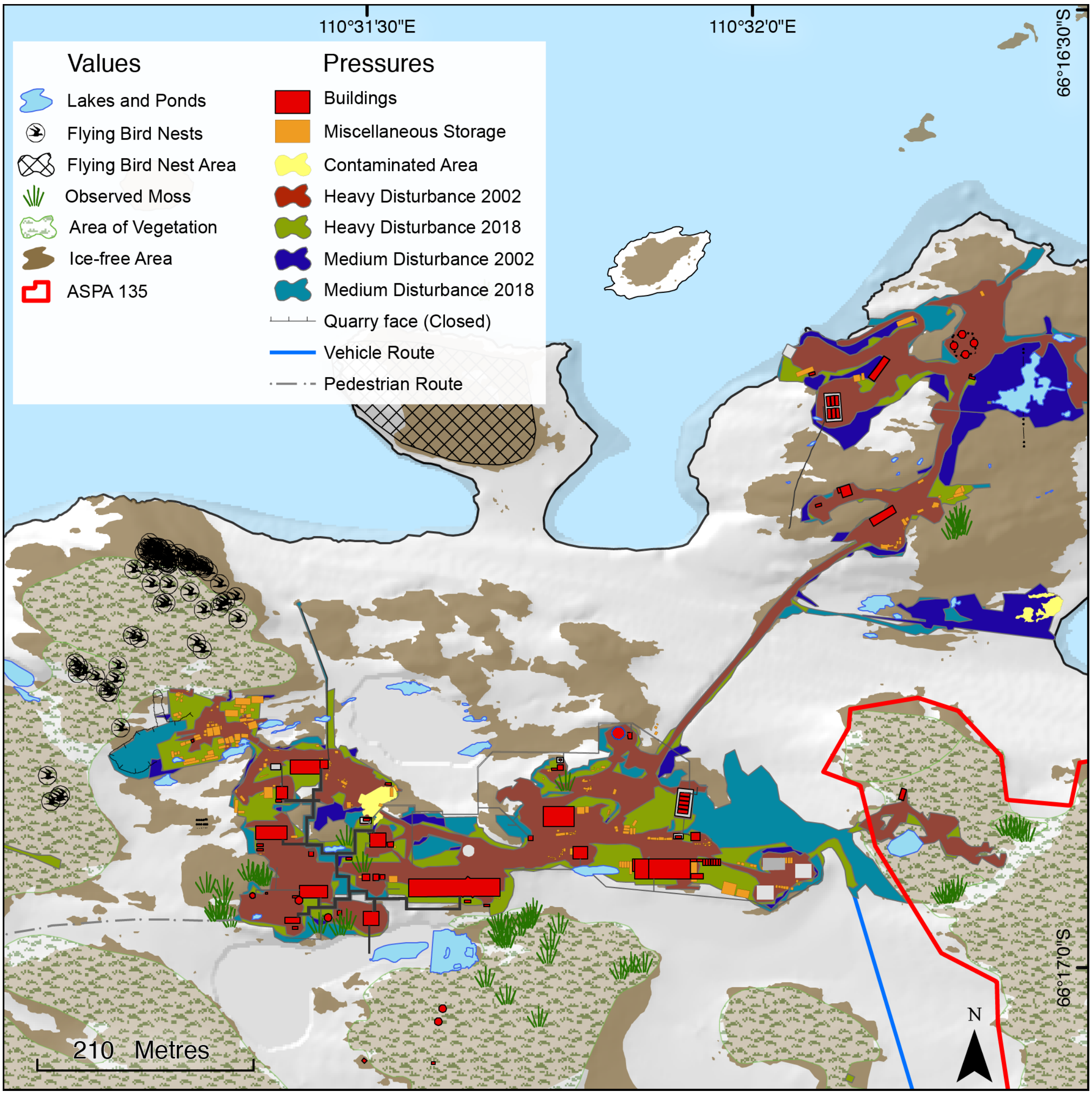

Figure 1: Map of Casey Station local area with select values and pressures illustrated. More values (*e.g.* invertebrate communities) are known within the station area, but were not included here due to the limited distribution of monitoring data. Identification of the differing areas of disturbance footprint between 2002 and 2018 is aided through the use of contrasting colours. Although the more significant instances of footprint change over time were verified, some variation will be due to differing snow cover and resolution between imagery dates. Horizontal Datum: WGS84. Projection: UTM Zone 49S. Disturbance footprint layers are original. Infrastructure, digital elevation model, routes, ASPA, and ice-free area data: Australian Antarctic Division. Remaining values and pressures layers produced from data sources listed in Supplementary Information 2. Produced by S. Brooks.

Figure 2: Area of moss growing within the southwest disturbance footprint of Casey Station. This colony is within a few metres of station buildings, however infrequent human activity in the area has enabled its establishment. Photo credit: Shaun Brooks.

station area (i.e. breeding or moulting), but haul-outs on nearby sea ice are common. Monitoring data of invertebrates within the station area were sporadic, however high densities of rotifers, tardigrades, nematodes, and mites have been recorded. The invertebrate data also demonstrated significant heterogeneity in their habitat requirements. The area has several geomorphological features of interest, including raised beach sequences, abandoned penguin colonies, and 42 lakes and ponds within the immediate vicinity of the station. These geomorphological features, along with the general climate of the region, are contributing factors for the dense concentrations of vegetation (Melick et al., 1994). While there are no designated historic sites within the station area, memorial crosses are located on nearby Reeves Hill, as well as some historic value in remnant buildings from the 1960s. Aesthetic values are present at Casey Station with its mix of glacial and ice-free landscapes, vegetation and fauna, resulting in a favoured ranking by expeditioners (tourism visitation is very rare) (Summerson, 2013). Wilderness values, however, are substantially effected in this region due to the visibility of extensive satellite infrastructure and antennae (Summerson, 2013).

Pressures

Casey Station is operated year-round and acts as an important logistical hub for Australian inter- and intracontinental flights. The median population for winter is 19 people, and 80 during summer (increasing slightly in the past decade). The station uses ~750,000 litres (l) of diesel per year across all infrastructure (generators, incinerators, and vehicles), with the monthly average increasing by ~15,000 l over the period reviewed (January 2009 to December 2015). Several significant fuel spills have occurred at Casey in recent years, although these were small in proportion to the total fuel handled (*e.g.* Brooks et al., 2018b; McWatters et al., 2016). Local sediments, including within the marine environment, also have concentrations of hydrocarbon and heavy metal contamination due to historic practices including in-situ waste disposal (Snape et al., 2001). Data was available for the biological oxygen demand and suspended solids in sewage discharge from 2009–2018, and were typically low compared to international standards (BOD median 26.25mg/l, SS 26.5 mg/l). This should also improve, with plans for modernisation of wastewater treatment at all Australian stations.

The footprint of Casey is significant, both as the eight largest station by built area in Antarctica and 15^{th} for disturbance (Brooks, 2018), and importantly for being situated within a location of concentrated vegetation values. Using the methodology from Brooks et al. (2019), I mapped medium- (similar to spoil) and heavy-intensity (similar to roads) disturbance footprint from imagery in 2002, 2008, 2015, and 2018 (see Supplementary Information 2). In January 2018, heavy disturbance footprint area was 72,002m^2, an increase of 18% over the preceding 16 years (Figure 1). Similarly, medium-intensity disturbance footprint, extending beyond the heavily impacted areas was 32,021m^2, an increase of 42% since 2002. Between 2008 and 2018, there was an increase of the building footprint of 1,670m^2 (27%), while over the same period 325m^2 (5%) of buildings were removed. These figures demonstrate pressure from the station's footprint has been increasing and will potentially further expand to support new traverse capabilities, logistical support, and maintenance needs in the near future (Price, 2019).

Although the Windmill Islands have a mild climate for East Antarctica, current modelling, even under RCP8.5 climate scenarios, show a low risk of non-native species establishment and ice-melt into the future (Duffy & Lee, 2019; Lee et al., 2017). This particular non-native species modelling, however, was limited to 24 species, and consistent incursion risks from human activities (*e.g.* Brooks et al., 2018b; Houghton et al., 2014) may provide enough pressure for a climatically tolerant species to become established. Indeed, a *Lycoriella* sp. fly is already established within the warmed conditions of station buildings (Hughes et al., 2005), and a further 12 taxa of fungal species have been found restricted to soil surrounding station buildings; suggesting human introduction (Azmi & Seppelt, 1998). Despite a small projected increase in ice-free land within the region by 2100 (Lee et al., 2017), this change may actually be detrimental to vegetation, with observations of a current drying trend already impacting moss health and distribution in the area (Robinson et al., 2018).

Conservation Planning

As a result of Casey Station's location and history, Figure 1 shows buildings and human activity are now closely surrounded by a mix of rich biological values. This is particularly pronounced due to the station site overlapping with the most important micro-climate for vegetation in the region: moist, nutrient-rich, northerly aspects, protected from high-salinity maritime winds (Melick et al., 1994). Although some of the densest moss beds are protected within nearby ASPA 135, these values are present throughout the station area. Similarly, there is no 'buffer' to protect the vegetation within the ASPA from adjacent human activity (Kriwoken, 1991), with a vehicle route traversing parallel to the protected area's boundary, and accidental incursions are known to have happened (Brooks et al., 2018b). Station activities in the past have also impacted vegetation health remotely due to wind-borne deposition of chemical dust (Adamson et al., 1994). As a consequence, conservation of vegetation values is warranted both inside and outside the ASPA. Furthermore, despite the region around Casey having the best records of biodiversity in Antarctica (Terauds et al., 2012), this case study revealed data points are still sporadic, collection is largely opportunistic, and monitoring has been predominately focussed within remaining intact natural areas. As a result, usefulness of existing data for detecting impacts from the station are limited, highlighting the invaluable information a comprehensive monitoring grid would provide for management and planning.

The growth in the footprint during the observation period reflects an increase in infrastructure, especially to meet increased accommodation requirements due to the establishment of an intercontinental air link, but also many small, incremental, and possibly unplanned, expansions into previously intact locations. Most examples where this was observed were infilling between previously forked infrastructure, or incremental outward 'creep'. The causation here was primarily expanding storage (*e.g.* more aviation fuel drums) or extending vehicle access routes (*e.g.* forming loops from terminuses). Although 'infilling' of areas within a station is a demonstrated approach to meet an expanding need for space while minimising footprint (Brooks et al., 2019), most instances observed here appear to have occurred on an *ad hoc* basis (*e.g.* no publicly-accessible EIAs were found for the observed expansions). As such, it cannot be determined if conservation of values was considered in planning these expansions. A dilemma also arises about whether natural values that have become established within 'disturbed' station environs warrant conservation (*e.g.* sheltered moist areas under elevated pipework at Casey have allowed dense areas of moss to establish).

To manage the need for continued use and to support expanding capabilities, the planning guidance provided through using systematic conservation planning may help station managers meet their objectives as well as improve conservation of values present within the immediate station area. Here, strategic planning for new areas to locate buildings and storage may be able to efficiently meet operational requirements with negligible increases in new footprint. For example, the site of the removed 1960s-era buildings, closer to the coast, had negligible biological values detected, has already been disturbed, and therefore may be better utilised to conserve significant vegetation elsewhere. Similarly, concentrated natural values were detected on the western, southern, and eastern boundaries of main station area, suggesting a possible need to limit any future expansion in these directions (Figure 1). Management of the incremental growth of footprint would also be beneficial, with clearly defined boundaries for vehicles, machinery, and storage to prevent the inadvertent creep of disturbance. Such boundaries may be either physical or administrative, depending on the circumstances, and should assist station managers and on-the-ground operators in their duties by preventing unintended deviation from already disturbed areas (such as during snow cover). Minimising the area of the necessary footprint may also help protect biological values in the face of climate change; reducing pressure from human activities could maximise their resilience to external changes, as well as providing more intact ground for potential range shifts into the future. Similarly, many problematic non-native plant species are ruderals, so minimisation of new disturbed ground may additionally help minimise or contain possible establishments.

Applying Systematic Conservation Planning to Stations

Operations

Through the process of developing this systematic conservation planning approach and our case study, many conservation issues, potential areas for improvements, and possibilities for decision-support were identified. Cumulative impacts from human activity, particularly from vehicles and machinery, were one of the most significant sources of ongoing disturbance-creating pressures around a station environment. In station environs where this pressure doesn't occur (*e.g.* rarely accessed areas behind buildings), biological values have remained or re-established (Figure 2). Learning from this observation, simple measures that delineate vehicle and pedestrian activity through a station could be one approach to allow the opportunity to increase conservation of values while having a negligible impact on day-to-day operations. These measures could include systematic conservation planning-developed designation of non-infrastructure use-areas such as container and material storage locations, parking, walking routes, and snow/spoil dumping areas, as well as tools to support those defined areas, including barriers for vehicles (*e.g.* bollards, large rocks, ropes lines) to prevent unintended incursions onto values, and defined paths for pedestrian movement including elevated walkways to pass over areas of values if necessary (as used at Dumont d'Urville Station). Information gained from systematic conservation planning may also assist decision making in regards to broader station management, including instances where opportunities to conserve values may provide enough weight to overcome inhibiting economic considerations such as 'sunk costs' in informing potential station redevelopments (*e.g.* Scott Base redevelopment; Willams, 2019). Similarly, through identifying a national program's conservation goals through the systematic conservation planning process, some objectives may be directly addressed with technological solutions (*e.g.* improved sewage treatment would address an objective of reducing pressure on the marine environment).

Monitoring

As a general hypothesis, any remnant natural values in a station area would be expected to be at their least in the centre of activity, and increase with distance outwards towards a baseline state. While this hypothesis is true in some instances (*e.g.* McMurdo Station; Klein et al., 2014), many stations still have rich values present within core areas (*e.g.* nesting birds at Dumont d'Urville, bryophyte vegetation at Casey, and vascular plants at Arctowski; Kozeretska et al., 2010; Melick et al., 1994; Micol & Jouventin, 2001). To maintain such values, as well as those on a station's periphery, monitoring is required to detect whether current conservation strategies (either active or passive) are effective, or to support decision making to take further planned actions to protect them. Although the Madrid Protocol requires station activities to 'be planned and conducted on the basis of (sufficient) information - about their possible impacts' (Article 3.2.c), there is not much evidence, in general, that targeted or effective monitoring (beyond vertebrates species) to meet this obligation across Antarctica is occurring (Hemmings & Kriwoken, 2010; Hughes, 2010; Wall et al., 2011). Furthermore, awareness of a station's footprint can be used to similar effect (Walton & Shears, 1994), but again, there are only a few examples of national programs meaningfully capturing this information (Brooks et al., 2018a).

From the consultation process during the development of this systematic conservation planning approach, the most prominent feedback from station managers was the desirability of information on weighting of values for conservation within the station environment to support decision making, especially in regard to balancing the compromise between environmental protection and developing station capabilities. Although the Madrid Protocol (and its Annexes), and the scientific literature, provide limited assistance for weighting of values (also see Supplementary Information 1), rigorous detection and monitoring would be essential to support such a process. Weighting of values may also be assisted through sophisticated modelling processes (*e.g.* IAATO & SCAR, 2019), however these may prove too complex for adoption of systematic conservation planning for stations across Antarctica unless a continent-wide dataset was provided. Readily accessible values and pressures data for station areas was also highly desirable, but current access was prevented by varied expertise in GIS-use between personnel, no single compilation of data layers, and general difficulty in sourcing information. Here, the majority of data found for the test application (Supplementary Information 2) were either already in GIS format, or easily translated into such, and could be compiled and made readily accessible across a national program through creation of a user-friendly web-based mapping portal. Such a development may also help identify what monitoring data are most useful for station management and conservation, subsequently informing more targeted collection into the future.

Administration

Systematic conservation planning offers a strategic approach to develop, implement, and manage any conservation objectives developed for a station. Documentation of how each stage of systematic conservation planning is addressed would be essential to assist guiding conservation actions. For a station-wide values-conservation plan, such documentation would form the basis of a management plan – a commonly-used tool for managing complex protected areas with competing demands. From the review conducted by this project, no publicly-accessible management plans were found for any Antarctic Stations, despite suggestions to use them predating the 1991 Madrid Protocol (*i.e*. Kriwoken, 1991). Building and engineering 'master plans' are used, but environmental planning arguably shouldn't be a latter consideration within a natural reserve. Similarly, fuel spill, non-native species, and legacy waste clean-up manuals have been developed, or are in the process (CEP, 2016; COMNAP, 2008), yet no guiding documentation exists for prescribing decisions, limits, or boundaries to the impacts of a station. As a consequence, conservation management for stations typically occurs on a reactive basis, with no guiding documentation provided, requiring assessments of activities which will have environmental impacts to be made dependant on individual staff knowledge and decisions.

A station management plan, created through systematic conservation planning, could provide a guiding document to assist day-to-day decision making by national programs. These would be developed from expert- and values-based data, to provide long-term station planning, prescribe areas for protection or potential use, and define limits and boundaries to development. Similarly, guidance provided by a management plan could deliver a long-term strategy that would avoid ongoing Preliminary Assessments (the lowest-level EIA under the Madrid Protocol), cumulatively resulting in impacts that are more than minor or transitory. In locations where multiple stations are present a joint conservation management plan would help coordinate efforts, especially in association with an Antarctic Specially Managed Area (ASMA). Although management plans are traditionally statutory documents, prescribed by law, this should not be necessary for stations, and instead provide an opportunity to streamline conservation management and decision making, simultaneously offsetting Antarctica's 'protected area' criticisms.

Conclusion

The footprint of stations in Antarctica, especially on ice-free areas, is growing. New stations, expanding infrastructure, and replacement of dated buildings is all contributing to this growth, with only a few examples of redundant stations being removed and the environment rehabilitated to offset this pressure. Simultaneously, climate change in the Antarctic is happening and its impacts are being observed. Here, reducing the pressure human activities have on vulnerable biological values may assist their resilience to a changing climate. Voluntary limits or boundaries need to be set by national programs around their stations or cumulative impacts will inevitably creep with time, further expanding footprint that displaces natural values. Planning to conserve extant values within a station's vicinity needs to be deliberate, and systematic conservation planning provides a framework to develop strategies to deliver it. The cost of fulfilling conservation planning, including the monitoring required to support it, would be low compared to the operational expense of running an Antarctic station, yet would provide multifaceted benefits for operators as well as streamlining compliance with their obligations under the Madrid Protocol. Ultimately, the use of systematic conservation planning to develop effective conservation management plans, with the capacity and commitment by a national program to apply it, would provide the best results for protecting the environment and most benefits for its operator.

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Tables

Table 1: The stages of Systematic Conservation Planning.

Figures

Figure 1: Map of Casey Station local area with select values and pressures illustrated.

Figure 2: Area of moss growing within the southwest disturbance footprint of the station.

Supplementary Information

Supplementary Information 1: Antarctic Research Station Systematic Conservation Planning Tool

Supplementary Information 2: Case Study Values and Pressures Data Sources

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Conclusion

Superficially, management of the impacts research stations have on the Antarctic continent – given its scale – may appear to be of little consequence against the environmental challenges faced globally. The state of the Antarctic environment, however, is important as it symbolises international co-operation, shared management without a sovereign, and a continental natural reserve that is mostly intact. Continuation of this status without active management should not be assumed though. Through finding that half of all large coastal ice-free areas are now disturbed, this thesis has revealed Antarctica has reached a crossroads where we need to choose what extent of footprint on the continent is acceptable into the future. Antarctic Treaty nations will need to decide whether we actively manage the extent of our footprint to minimise the necessary disturbance, particularly for ice-free land, or if we allow impacted sites to continue to spread, subsequently diminishing the number of inviolate areas for natural processes, dependant ecosystems, and future scientific reference. As the purpose of most infrastructure on the continent is to support science, and to a lesser extent ecotourism, these uses should also set leading examples of conservation planning: enabling access to the continent while minimising impacts to the natural values they primarily seek.

To assist Treaty nations to address these issues, this thesis has provided a significant contribution towards conservation planning for Antarctic stations. It has:

- defined types of *footprint* in Antarctica, supporting further conservation and environmental management use;
- investigated contemporary environmental incidents at station sites, identifying that, apart from fuel spills, few impacts with significant consequences arose from accidents. Over the same period, however, the footprint of the case study station increased, indicating planned activities are probably the greater source of substantial impacts;
- provided the first continent-wide building and disturbed ground footprint dataset;

- analysed the footprint of stations across the continent, identifying planning strategies that reduce disturbance, and its implications for the Antarctic Conservation Biogeographical Regions (ACBRs) and Antarctic Specially Protected Areas (ASPAs);
- validated that visibly disturbed ground provides a proxy which identifies further human impacts, beyond aesthetic and wilderness values, across the continent; and
- provided a structure to assist systematic conservation planning for research stations.

If the footprint from construction of new or expanding stations continues to follow its current growth trajectory, strategic planning will be needed for where it occurs, and consideration given to limits or boundaries to development to meet the Protocol's environmental obligations. This is relevant, both for science, where stations in close proximity create overlapping access, and for conservation, with human impacts already spread disproportionately between the ACBRs. The distribution of stations across the continent should be systematically managed and co-ordinated so new facilities provide access to areas that enable novel and relevant science, and excessive impacts to certain natural values or representative environments are avoided. Conservation planning for stations would also benefit from further collaboration with efforts to expand the coverage of ASPAs, as significant overlap exists between the objectives and data collection required by these projects. Ultimately, better planning of where stations are located, and greater use of previously disturbed sites, would benefit access while simultaneously minimising the necessary impacts to natural values. At an individual station level, conservation planning is not necessarily an expensive proposition (especially compared to remediation programs), but it does need to be prioritised and deliberate. By implementing conservation planning, permitting and managing operations may actually be made more efficient by providing improved guidance to usage of the station environment. In addition, explicit conservation planning offers further benefits to station operators, including the potential for protecting natural resources (such as potable water availability where melt is harvested), and improved aesthetics of station environments, enhancing the perceptions and attitudes of expeditioners and observers.

For effective local and continent-wide conservation planning for Antarctic stations to occur, data on pressures is essential, particularly within the spatial form of footprint. Prior to this thesis, spatial data on the pressure from stations were limited to a few locations across the continent. Although this has now been addressed by providing a comprehensive dataset for building and disturbed ground, this has only captured a fixed window in time. As a consequence, ongoing updates and improved accuracy is desirable to support regional scale conservation planning. Similarly, the resolution of this dataset can be improved through input of on-the-ground survey data or mapping which uses higher resolution imagery (such as from unmanned aerial vehicles). Accessibility of this data to decision-makers can also be enhanced, especially if adopted to become a standard set of information within a portal such as the Antarctic Digital Database (https://www.add.scar.org), Antarctic Environments Portal (https://www.environments.aq/map), or dissemination through organisations such as COMNAP.

Through revealing the footprint on Antarctica for the first time, this thesis has dispelled popular notions of a pristine continent. Although the ice environment still provides great wilderness areas, aligning with such perceptions of Antarctica, ice-free land is under pressure. With interest in increasing access across Antarctica, national programs – the custodians, land managers, and source of most environmental impacts – will need to be more active in meeting their responsibility to effectively protect the Antarctic environment in a way that is consistent with public expectations for the continent, and its designation as a natural reserve devoted to peace and science.

Supplementary Material

Chapter 2

Table 1: IHIS impact determination matrix.

Critical	High	Medium	Low	Insignificant	NI (No applicable impact)
Severe environmental impacts that are widespread (regional) or of long-term/permanent duration	Serious environmental impact that cover a broad area or of medium-term duration	Limited environmental impact s that are localised or of short-term duration	Negligible environmental impacts that are restricted to the immediate area and of brief duration	No observable environmental impacts	Not applicable

Chapter 3

Supplementary Table 1. *Footprint measurements for locations.*

Name	Year Opened	Latitude	Longtitude	Type	Status	Min pop	Max pop	Data_Source	Date_of_image	Buildings	Disturbance	Ratio
Aboa	1989	-73.0423	-13.4074	Station	Year-round		20	Estimate - photography	19/11/2010	**122**	**122**	
ALCI Airbase & Whichaway Camp	2006	-70.8231	11.6435	Camp	Seasonal			CNES/Airbus	21/12/2016	**622**	**10914**	17.5:1
Amundsen-Scott South Pole Station	1956	-89.9975	139.2728	Station	Seasonal	75	250	NASA DMS Operation Icebridge	4/11/2010	**35017**		
Arctowski	1977	-62.1598	-58.4733	Station	Seasonal	12	40	Digital Globe	21/01/2014	**3351**	**32002**	9.5:1
Artigas	1984	-62.1846	-58.9024	Station	Year-round	9	60	Digital Globe	16/01/2014	**1857**	**49590**	26.7:1
Arturo Prat	1947	-62.4793	-59.6635	Station	Year-round	9	15	Digital Globe	27/12/2011	**2073**	**8584**	4.1:1
Asuka	1984	-71.5263	24.1125	Station	Year-round			Digital Globe	11/10/2012	**31**		
Belgrano II	1955	-77.8744	-34.6269	Station	Seasonal	12	12	Digital Globe	22/11/2009	**1183**	**6729**	5.6:1
Bellingshausen	1968	-62.1982	-58.9606	Station	Year-round	25	38	Digital Globe	27/01/2012	**4463**	**160125**	35.8:1
Bernardo O'Higgins Riquelme	1948	-63.3210	-57.8998	Station	Seasonal	16	44	Digital Globe	25/01/2015	**3228**	**18837**	5.8:1
Bharati	2012	-69.4000	76.1830	Station	Seasonal	15		Digital Globe	18/01/2011	**2008**	**20313**	10.1:1
Brown	1951	-64.8954	-62.8705	Station	Year-round		18	Digital Globe	4/11/2009	**305**	**630**	2:1
Browning Pass	1997	-74.6229	163.9152	Camp	Seasonal		2	Digital Globe	4/11/2014	**78**		
Byrd Surface	1957	-80.0139	-119.5614	Camp	Seasonal			Digital Globe	2/10/2009	**112**		
Cámara	1953	-62.5939	-59.9193	Station	Seasonal		36	Digital Globe	20/02/2010	**693**	**4762**	6.8:1
Cap Prud'homme	1994	-66.6876	139.9072	Camp	Year-round		20	Digital Globe	7/12/2011	**1682**	**750**	
Carlini (formally known as Jubany)	1982	-62.2379	-58.6668	Station	Year-round	20	100	Digital Globe	21/03/2011	**3678**	**54867**	14.9:1
Casey	1969	-66.2823	110.5268	Station	Year-round	20	70	Digital Globe	16/02/2012	**9233**	**99599**	10.7:1
Comandante Ferraz	1984	-62.0846	-58.3926	Station		12	40	Digital Globe	21/01/2014	**2636**	**15779**	5.9:1
Concordia	1997	-75.1000	123.3326	Station	Seasonal	13	60	Digital Globe	1/11/2014	**6189**		
Davis	1957	-68.5759	77.9695	Station	Seasonal	22	70	Digital Globe	26/12/2012	**10735**	**137239**	12.7:1
Decepcíon	1948	-62.9768	-60.7007	Station	Seasonal		65	Digital Globe	29/12/2013	**1291**	**24781**	19.1:1
Dome Fuji	1995	-77.3171	39.6988	Station	Year-round		15	Digital Globe	14/11/2009	**727**		
Druzhnaya-4	1987	-69.7478	73.7092	Station	Seasonal		50	Estimate - photography	15/02/2002	**528**	**528**	
Dumont d'Urville	1956	-66.6628	140.0013	Station	Year-round	26	100	Digital Globe	16/12/2011	**7664**	**117618**	15.3:1
Edgeworth David	1986	-66.2499	100.6042	Camp	Year-round			Digital Globe	27/01/2012	**40**	**40**	
Eduardo Frei Montalva	1969	-62.2002	-58.9626	Station	Year-round	70	120	Digital Globe	16/01/2014	**6287**	**113746**	18:1
Enigma Lake	2005	-74.7192	164.0277	Airfield Camp	Seasonal			Digital Globe	4/11/2014	**35**	**5652**	161.4:1
Esperanza	1952	-63.3970	-56.9981	Station	Seasonal	55	90	Digital Globe	5/02/2011	**3854**	**67636**	17.5:1
Fossil Bluff	1961	-71.3234	-68.2891	Camp	Seasonal		6	Digital Globe	14/10/2012	**112**	**1277**	11.4:1
Gabriel de Castilla	1990	-62.9772	-60.6757	Station	Seasonal		25	Digital Globe	29/12/2013	**926**	**8540**	9.2:1
Gondwana	1983	-74.6355	164.2212	Station	Seasonal			Digital Globe	4/11/2014	**383**	**383**	
Great Wall	1985	-62.2164	-58.9644	Station	Year-round	14	40	Digital Globe	16/01/2014	**4769**	**78665**	16.4:1
Halley IV	1956	-75.5798	-26.7286	Station	Seasonal	15	65	Digital Globe	13/02/2011	**3056**		
International Field Camp Peninsula Byers	2001	-62.6583	-61.0933	Camp	Seasonal		12	Digital Globe	5/12/2010	**37**	**128**	3.4:1
Jang Bogo	2014	-74.6167	164.2000	Station	Year-round	16	60	Digital Globe	4/11/2014	**10333**	**110957**	10.7:1
Johann Gregor Mendel	2006	-63.8006	-57.8826	Station	Seasonal		20	Digital Globe	25/01/2015	**497**	**4027**	8.1:1
Juan Carlos I	1989	-62.6634	-60.3881	Station	Seasonal		25	Digital Globe	29/12/2013	**2557**	**29251**	11.4:1
Julio Escudero	1994	-62.2014	-58.9627	Station	Seasonal	2	26	Digital Globe	16/01/2014	**1248**	**9858**	7.8:1
King Sejong	1988	-62.2232	-58.7865	Station	Seasonal	18	70	Digital Globe	21/03/2011	**5861**	**75383**	12.8:1
Kohnen	2001	-75.0019	0.0667	Station	Seasonal		28	CNES/Astrium	17/11/2016	**1432**		
Kunlun	2009	-80.4169	77.1161	Station	Year-round		20	Digital Globe	28/12/2010	**625**		
Law	1987	-69.3883	76.3807	Station	Seasonal		13	Digital Globe	18/01/2011	**61**	**61**	
Leningradskaya	1971	-69.5015	159.3911	Station	Seasonal			Digital Globe	3/12/2011	**1584**	**1584**	
Lieutenant Arturo Parodi	1999	-80.3119	-81.3666	Station	Seasonal		25	Digital Globe	3/10/2009	**929**		
Lieutenant Luis Carvajal Villarroel	1985	-67.7613	-68.9148	Station	Seasonal		30	Digital Globe	1/03/2011	**368**	**6388**	17.3:1
Lieutenant Rodolfo Marsh M. Aerodrome	1969	-62.1937	-58.9800	Airfield Camp	Seasonal	8	15	Digital Globe	16/01/2014	**2650**	**220408**	83.1:1
Luis Guillermo Mann (also "Shirriff Base")	1991	-62.4500	-60.7833	Station	Seasonal		6	Digital Globe	6/03/2014	**345**	**5175**	15:1
Machu Picchu	1989	-62.0916	-58.4706	Station	Year-round		28	Digital Globe	21/01/2014	**882**	**10754**	12.1:1
Maitri	1989	-70.7668	11.7308	Station	Year-round	25	65	CNES/Astrium	2/11/2016	**5060**	**76004**	15:1
Maldonado	1990	-62.4493	-59.7410	Station	Seasonal		22	Digital Globe	20/02/2010	**973**	**16945**	17.4:1
Marambio	1969	-64.2418	-56.6232	Station	Year-round	55	150	Digital Globe	16/01/2012	**10350**	**563188**	54.4:1
Marble Point Heliport	1956	-77.4137	163.6792	Airfield Camp	Seasonal			Digital Globe	21/01/2012	**1096**	**195580**	178.4:1
Mario Zucchelli	1986	-74.6948	164.1133	Station	Seasonal		90	Digital Globe	4/11/2014	**8439**	**86614**	10.2:1
Matienzo	1961	-64.9759	-60.0709	Station	Seasonal		15	Digital Globe	4/10/2011	**1073**	**12573**	11.7:1
Mawson	1954	-67.6026	62.8730	Station	Seasonal	20	60	Digital Globe	9/02/2006	**9491**	**94179**	9.9:1
McMurdo Station	1955	-77.8482	166.6684	Station	Seasonal	250	1000	Digital Globe	5/01/2012	**89638**	**1162925**	12.9:1
Melchior	1947	-64.3257	-62.9763	Station	Seasonal		36	Digital Globe	27/02/2012	**398**	**2011**	5:1
Mid Point (Charlie)	1998	-75.5417	145.8204	Camp	Seasonal			Digital Globe	1/02/2010	**73**		
Mirny	1956	-66.5582	93.0004	Station	Seasonal	60	169	Digital Globe	2/01/2006	**4877**	**139018**	28.5:1
Mizuho	1970	-70.6990	44.2778	Station	Seasonal			Digital Globe	10/10/2012	**24**		
Molodezhnaya	1962	-67.6654	45.8420	Station	Year-round			Digital Globe	15/02/2006	**8824**	**68834**	7.8:1
Molodezhnaya Airfield	1962	-67.6697	45.8286	Airfield	Year-round			Digital Globe	15/02/2006	**6134**	**27269**	4.4:1
Mountain Evening	2006	-67.6583	46.1533	Station	Seasonal		12	Digital Globe	15/02/2006	**190**	**552**	2.9:1
Neumayer III	1981	-70.6773	-8.2716	Station	Year-round	9	50	Digital Globe	6/01/2012	**3045**		
Novolazarevskaya	1961	-70.7769	11.8237	Station	Seaonal	30	70	CNES/Astrium	2/11/2016	**3336**	**57938**	17.3:1
Novolazarevskaya Airfield	1961	-70.8218	11.6399	Airfield	Year-round			CNES/Astrium	2/11/2016	**2802**		
Oazis	1956	-66.2667	100.7333	Station	Year-Round			Digital Globe	11/02/2011	**462**	**2686**	5.8:1
Odell Glacier Camp	1985	-76.6601	159.9532	Camp	Seasonal			Digital Globe	7/12/2011	**9**		
Ohridski	1988	-62.6407	-60.3652	Station	Year-round		18	Map by Lyubomir Ivanov/Digital Globe	2014 & 29/12/2013	**309**	**2533**	8.1:1
Orcadas	1904	-60.7376	-44.7374	Station	Seasonal	14	45	Digital Globe	25/02/2011	**2528**	**63045**	24.9:1
Palmer Station	1965	-64.7743	-64.0533	Station	Year-round	12	43	Digital Globe	16/01/2014	**2629**	**11234**	4.2:1
Petrel	1967	-63.4783	-56.2310	Station	Seasonal		55	Digital Globe	22/02/2010	**2965**	**8745**	2.9:1
President Gabriel Gonzalez Videla	1951	-64.8239	-62.8575	Station	Seasonal		9	Digital Globe	6/12/2013	**765**	**765**	
Primavera	1977	-64.1559	-60.9543	Station	Year-round		18	Digital Globe	7/02/2012	**423**	**832**	1.9:1
Princess Elisabeth	2009	-71.9499	23.3469	Station	Seasonal		20	Digital Globe	11/10/2012	**2045**	**798**	
Progress	1989	-69.3781	76.3878	Station	Seasonal	20	77	Digital Globe	18/01/2011	**10573**	**161984**	15.3:1
Rada Covadonga		-63.3207	-57.8982	Station	Seasonal			Digital Globe	25/01/2015			
Republica del Ecuador	1990	-62.1210	-58.3952	Refuge	Year-round		4	Digital Globe	21/01/2014	**117**	**117**	
Ripamonti	1982	-62.2102	-58.9347	Station	Seasonal			Digital Globe	16/01/2014	**66**	**10659**	161.5:1
Risopatrón	1957	-62.3785	-59.7007	Station	Year-round		8	Digital Globe	11/04/2013	**114**	**1525**	13.3:1
Rothera	1975	-67.5686	-68.1244	Station	Year-round	22	130	Digital Globe	21/01/2011	**8258**	**176732**	21.4:1

Rothera Skiway	1975	-67.5676	-68.1272	Airfield Camp	Seasonal			Digital Globe	21/01/2011			
Ruperto Elichiribehety	1997	-63.4024	-56.9909	Station	Seasonal			Digital Globe	5/02/2011	**278**	**4186**	15:1
Russkaya	1980	-74.7657	-136.8001	Station	Year-round			Digital Globe	31/10/2012	**1437**	**16200**	11.2:1
S17 Camp	2005	-69.0281	40.0924	Camp	Year-round			Digital Globe	15/11/2009	**627**		
San Martín	1951	-68.1303	-67.1029	Station	Seasonal	20	20	Digital Globe	12/03/2011	**1272**	**8801**	6.9:1
SANAE IV	1962	-71.6729	-2.8403	Station	Seasonal	10	80	Digital Globe	6/02/2012	**4376**	**30507**	6.9:1
Scott Base	1957	-77.8494	166.7673	Station	Seasonal	10	85	Digital Globe	5/01/2012	**6763**	**95483**	14.1:1
Signy	1947	-60.7083	-45.5954	Station	Seasonal		10	Digital Globe	22/02/2013	**803**	**4266**	5.3:1
Siple Dome	1996	-81.6543	-149.0051	Camp	Year-round			Digital Globe	3/12/2010	**882**		
Sky Blu	1993	-74.8564	-71.5852	Airfield Camp	Seasonal		6	Digital Globe	11/10/2012	**69**		
Soyuz	1982	-70.5766	68.7949	Station	Seasonal			Digital Globe	18/01/2012	**485**	**22836**	47:1
Svea	1987	-74.5761	-11.2249	Station	Year-round			Digital Globe	1/12/2011	**12**	**12**	
Syowa	1957	-69.0041	39.5818	Station	Seasonal	28	110	Digital Globe	11/02/2010	**8667**	**319074**	36.8:1
Taishan	2014	-73.8639	76.9747	Camp	Year-round		5	Landsat/Copernicus	31/12/2014	**948**		
Tor	1985	-71.8895	5.1599	Refuge	Seasonal		4	Digital Globe	2/12/2011	**59**	**59**	
Troll	1990	-72.0119	2.5331	Station	Seasonal	7	40	Digital Globe	26/11/2013	**5264**	**58584**	11.1:1
Union Glacier	2010	-79.7567	-82.8293	Airfield/Camp	Seasonal		100	Digital Globe	4/12/2009	**30**		
Vernadsky	1996	-65.2457	-64.2575	Station	Seasonal	12	24	CNES/Airbus	17/11/2016	**1107**	**6045**	5.4:1
Vostok	1957	-78.4642	106.8380	Station	Seasonal	13	25	Digital Globe	5/01/2014	**3247**		
WAIS Divide	2005	-79.4713	-112.0722	Camp	Seasonal		40	Digital Globe	11/02/2010	**1180**		
Wasa	1989	-73.0428	-13.4129	Station	Year-round		20	Photo estimate	2012	**224**	**224**	
Wilkins Aerodrome	2006	-66.6897	111.4846	Airfield Camp	Year-round			Digital Globe	2/02/2012	**1641**		
Yelcho	1962	-64.8759	-63.5838	Station	Year-round			Digital Globe	12/03/2011	**107**	**1481**	13.8:1
Zhongshan	1989	-69.3733	76.3778	Station	Year-round	15	30	Digital Globe	18/01/2011	**7868**	**162130**	20.6:1
Lake Hoare - Dry Valleys	1979	-77.6232	162.9004	Camp	Seasonal			Digital Globe	16/11/2008	**248**	**5502**	
Vinson Camp	1987	-78.5333	-86.0167	Camp	Seasonal			Digital Globe	11/01/2010	**190**	**0**	
Lake Bonney Camp - Dry Valleys	1989	-77.7144	162.4422	Camp	Seasonal			CNES/Airbus	12/11/2016	**171**	**1948**	
Lake Fryxell Camp - Dry Valleys	1987	-77.6058	163.1256	Camp	Seasonal			Digital Globe	18/01/2010	**159**	**1526**	
New Harbor - Dry Valleys	1982	-77.5778	163.5204	Camp	Seasonal			Digital Globe	18/01/2010	**117**	**745**	
Groussac Refuge	1955	-65.1758	-64.1359	Refuge				CNES/Airbus	17/11/2016	**70**	**70**	
Mt Newall - Dry Valleys	<1984	-77.5042	162.6250	Hut	Radio Repeater			Digital Globe	16/11/2008	**69**	**69**	
Cape Roberts Camp - Dry Valleys	<2004	-77.0391	163.1756	Camp	Seasonal			Digital Globe	8/11/2008	**68**	**68**	
F-6 Camp	1994	-77.6088	163.2580	Camp	Seasonal			Digital Globe	18/01/2010	**61**	**4795**	
Bull Pass Hut - Dry Valleys	<1993	-77.5173	161.8503	Hut	Seasonal			CNES/Airbus	9/12/2013	**57**	**57**	
Refugio Ballve	1953	-62.2167	-58.9333	Refuge				Digital Globe	5/10/2011	**44**	**508**	
Base Gurruchaga , Nelson Island	1954	-62.2500	-59.0000	Hut	Seasonal			Digital Globe	21/02/2006	**42**	**42**	
Lake Vanda Hut - Dry Valleys	1967	-77.5221	161.6834	Hut	Seasonal			CNES/Airbus	22/11/2016	**40**	**4819**	
Lower Wright Valley - Dry Valleys	1984	-77.4424	162.6507	Camp	Seasonal			Digital Globe	16/11/2008	**21**	**186**	
Unknown Hut	2014	-62.2305	-58.9848	Hut				Digital Globe	16/01/2014	**12**	**32**	
Rasmussen Hut	1984	-65.2500	64.1000	Hut				CNES/Airbus	17/11/2016	**11**	**11**	
Beaver Lake	1995	-70.8030	68.1798	Camp	Seasonal			Estimate	3/02/2017	**10**	**10**	
Refuge Libertador General San Martín EA	1955	-64.1879	-58.3855	Refuge				Digital Globe	13/09/2010	**8**	**8**	
Refugio San Carlos EA	1959	-63.8341	-58.0215	Refuge				Digital Globe	25/01/2015	**7**	**7**	
Refugio Ensenada Martel ARA	1947	-62.1017	-58.4621	Refuge				Digital Globe	5/10/2011	**59**	**59**	
Captain Pieter J. Lenie Base	1985	-62.1783	58.4458	Station	Seasonal			Digital Globe	4/09/2008	**208**	**655**	
Base F' (Wordie House)	1947	-64.2554	-65.2511	HSM	62			CNES/Airbus	17/11/2016	**87**	**223**	
Cemetery on Buromskiy Island	1974	-66.5344	93.0000	HSM	9			Digital Globe	28/10/2011	**4**	**273**	
Observatory at Bunger Hills	1956	-66.2750	100.7508	HSM	10			Digital Globe	11/02/2011	**14**	**14**	
Hut at Cape Royds, Ross Island	1908	-77.5500	166.1667	HSM	15			Digital Globe	24/02/2011	**29**	**29**	
Hut at Cape Evans, Ross Island	1911	-77.6333	166.4000	HSM	16			Digital Globe	5/01/2012	**632**	**2216**	
Hut at Hut Point, Ross Island	1902	-77.8333	166.6167	HSM	18			Digital Globe	5/01/2012	**137**	**Within Station**	
Hut at Cape Adare, Borchgrevink Coast	1899	-71.3000	170.2000	HSM	22			Digital Globe	12/11/2011	**98**	**277**	
Hut on Snow Hill Island	1902	-56.9910	-64.3637	HSM	38			Digital Globe	17/10/2012	**78**	**157**	
Hut and grave on Paulet Island	1903	-55.7845	-63.5747	HSM	41			Digital Globe	21/10/2005	**122**	**122**	
Buildings and artefacts on Stonington Island	1939	-67.0000	-68.1833	HSM	55			Digital Globe	12/03/2011	**163**	**1084**	
Plaque and cairn at 'Penguins Bay'	1903	-56.6500	-64.2667	HSM	60			Digital Globe	12/03/2011	**227**	**550**	
Base Y' on Horseshoe Island	1955	-67.3000	-67.8000	HSM	63			Digital Globe	24/02/2012	**314**	**380**	
Base E' on Stonington Island	1946	-67.0000	-68.1833	HSM	64			Digital Globe	12/03/2011	**429**	**3068**	
Whaling station, Deception Island	1906	-60.5667	-62.9833	HSM	71			Digital Globe	29/12/2013	**3475**	**10943**	
Cape Denison	1912	-67.0083	142.6611	HSM	77			Digital Globe	5/02/2011	**207**	**230**	
Lillie Marleen Hut, Mt. Dockery	1979	-71.2000	164.5167	HSM	79			Digital Globe	31/01/2012	**20**	**20**	
Base W', Detaille Island	1956	-66.8000	-66.8667	HSM	83			Digital Globe	28/12/2011	**231**	**231**	
Hut at Damoy Point	1973	-63.5167	-64.8167	HSM	84			Digital Globe	5/10/2010	**75**	**280**	
Wilkes	1959	-66.4167	110.9667	Station	Abandoned			Digital Globe	30/01/2011	**1977**	**1977**	
Cape Hallett	1957	-72.7000	170.4500	Station	Removed			Digital Globe	1/03/2010		**2552**	
Ardley Island Lighthouse	-	-62.2106	-58.9262	Lighthouse				Digital Globe	21/02/2013	**2**	**2**	
Buenos Aires Lighthouse	-	-64.8885	-63.9465	Lighthouse				Digital Globe	16/01/2014	**4**	**45**	
Collins Point Lighthouse	-	-62.9958	-60.5865	Lighthouse				Digital Globe	29/12/2013	**3**	**3**	
Edwards Point Lighthouse	-	-62.4609	-59.5133	Lighthouse				Digital Globe	11/04/2013	**2**	**2**	
Fort William Lighthouse	-	-62.3703	-59.7231	Lighthouse				Digital Globe	11/04/2013	**3**	**3**	
Grumete Lighthouse	-	-62.9799	-60.6607	Lighthouse				Digital Globe	16/10/2010	**2**	**7**	
Condell Lighthouse	-	-64.8167	-63.0917	Lighthouse				Digital Globe	4/11/2009	**5**	**5**	

Note: Type, Status, and Population derived from COMNAP 2017.

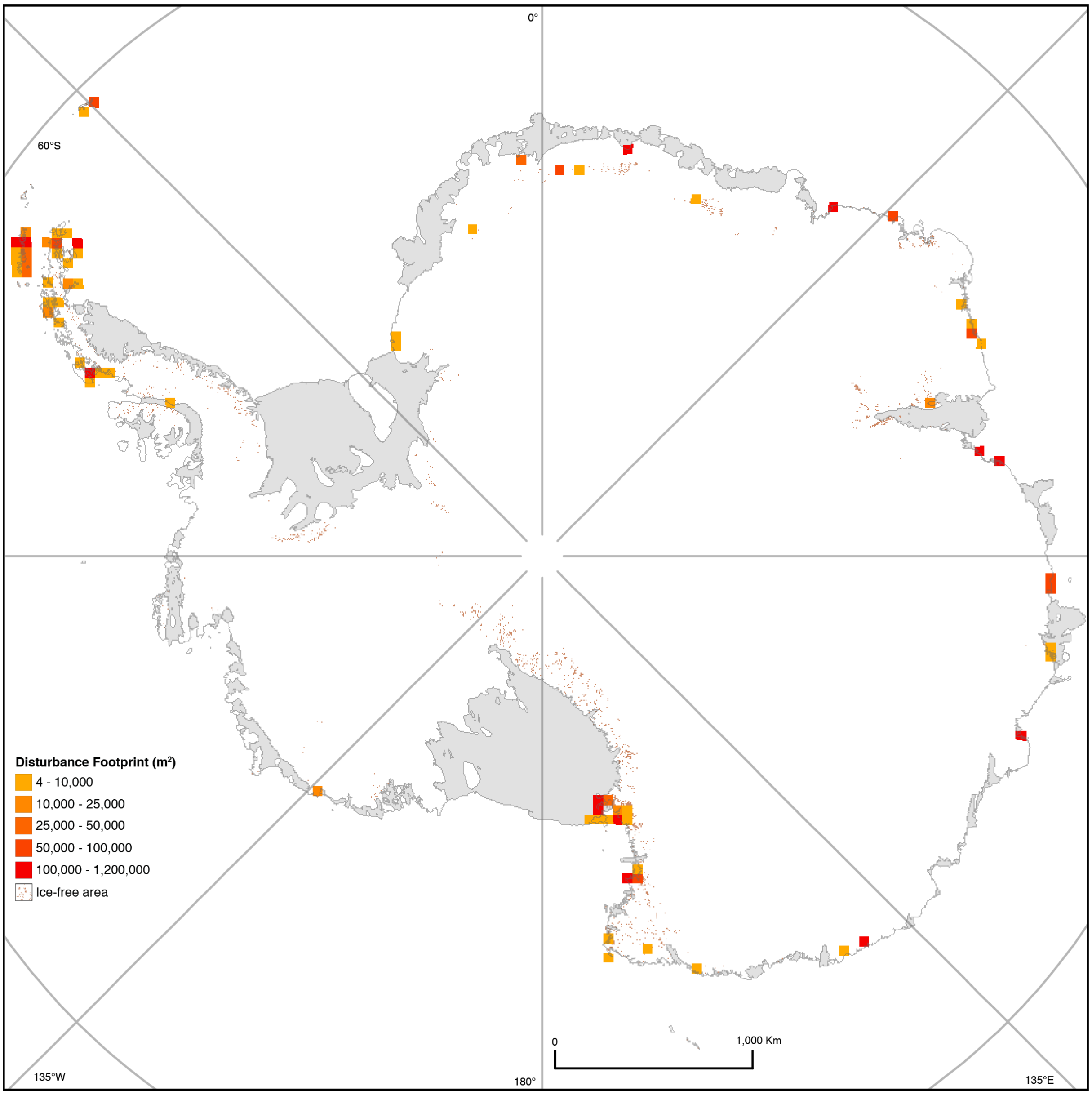
Supplementary Table 2. *Footprint measured for each Antarctic Conservation Bioregion*

ACBR identifier	ACBR name	Total ACBR area (km^2)	Building Footprint (m^2)	Disturbance Footprint (km^2)	% of ACBR covered by disturbance footprint
ACBR1	North-east Antarctic Peninsula	1215	13157	0.6392	0.053
ACBR2	South Orkney Islands	160	682	0.0673	0.042
ACBR3	North-west Antarctic Peninsula	5183	62638	1.2109	0.023
ACBR4	Central South Antarctic Peninsula	4962	112	0.0013	0.000
ACBR5	Enderby Land	2188	20915	0.4157	0.019
ACBR6	Dronning Maud Land	5523	16523	0.2348	0.004
ACBR7	East Antarctica	1109	35520	0.7254	0.065
ACBR8	North Victoria Land	9431	19126	0.2127	0.002
ACBR9	South Victoria Land	10038	87953	1.4759	0.015
ACBR10	Transantarctic Mountains	18480	1183	0.0067	0.000
ACBR11	Ellsworth Mountains	2859	0	0	0.000
ACBR12	Marie Byrd Land	1128	1437	0.0162	0.001
ACBR13	Adelie Land	178	7164	0.1186	0.067
ACBR14	Ellsworth Land	217	0	0	0.000
ACBR15	South Antarctic Peninsula	2875	0	0	0.000
ACBR16	Prince Charles Mountains	5992	9141	0.1170	0.002

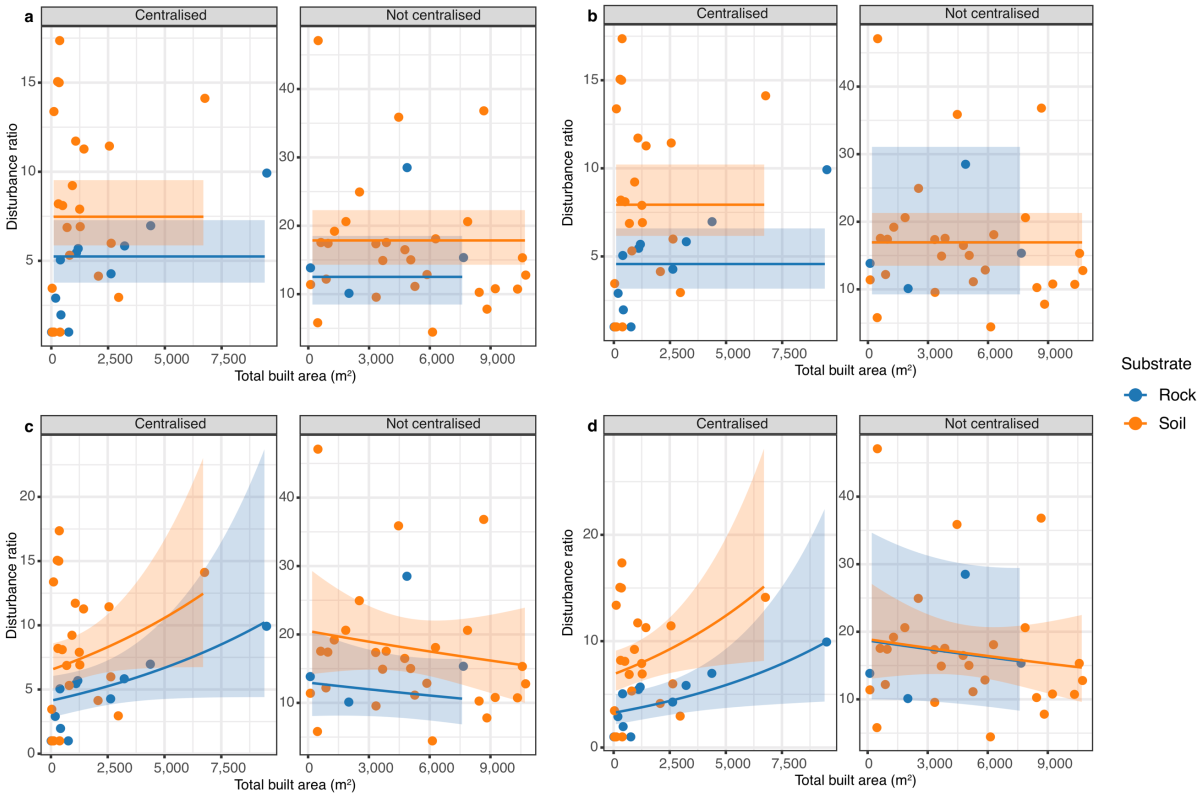
Supplementary Table 3. *Summary of all models examined.*

"Model terms" indicates the model structure (+ indicates main effects, * indicates interaction terms). AIC gives the Akaike information criterion for the model, and delta AIC gives the difference of that model from the best. The four models indicated by # were all considered plausible, and used for further analysis.

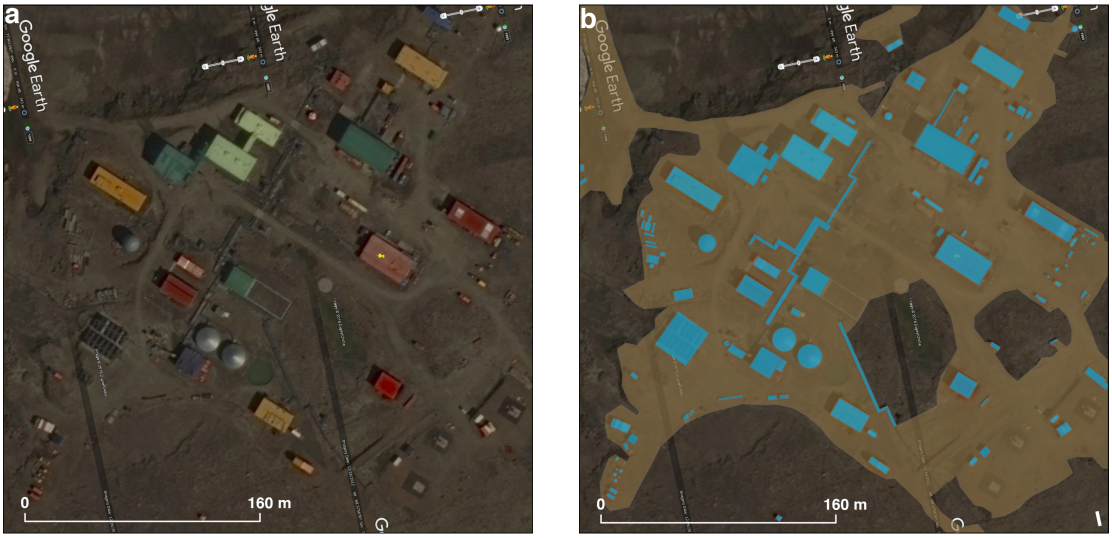
Model	**Model terms**	**AIC**	**delta AIC**
A	Intercept only	1399.9	27.9
B	configuration	1375.1	3.1
C	substrate	1397.4	25.4
D	size	1397.5	25.6
E#	substrate + configuration	1373.8	1.8
F	substrate + size	1394.5	22.5
G	configuration + size	1377.1	5.1
H	substrate + configuration + size	1375.6	3.6
I#	substrate * configuration	1373.8	1.8
J	size * configuration	1377.0	5.1
K	substrate * configuration + size	1375.3	3.3
L#	configuration * size + substrate	1373.6	1.6
M#	substrate * configuration + configuration * size	1372.0	0



Supplementary Fig. 1. *Continent disturbance footprint presented in 50x50km² cells.*

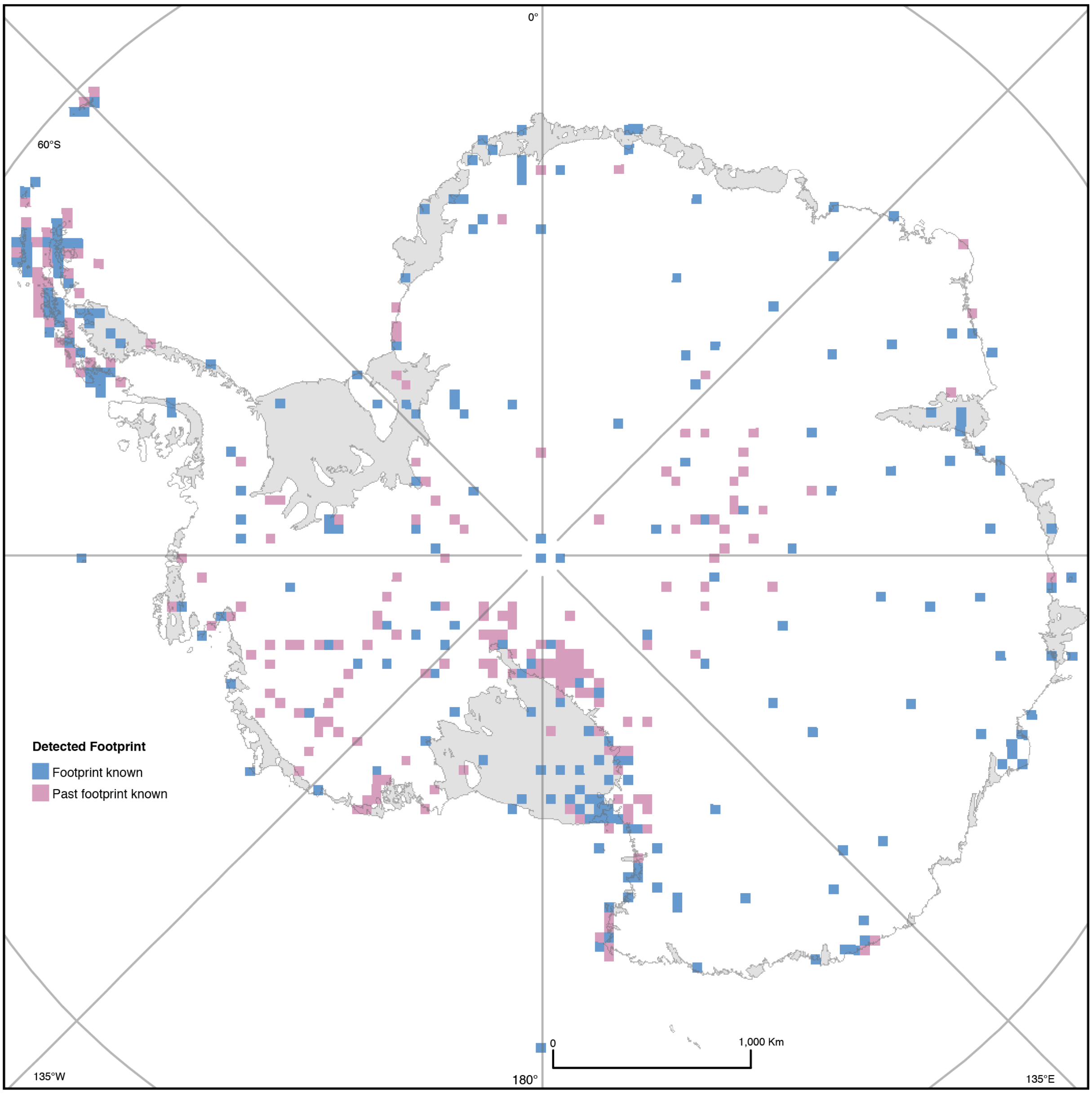


Supplementary Fig. 2. *Plot of Disturbance to Building Footprint ratios for centralised and decentralised station configurations.* The four panels show the fits of the four plausible models to the data (see Statistical Analysis section). The shaded bands show 95% confidence intervals. The models are **a**) E, **b**) I, **c**) L, and **d**) M (see Supplementary Table 3). Note: differing y-axis scales.



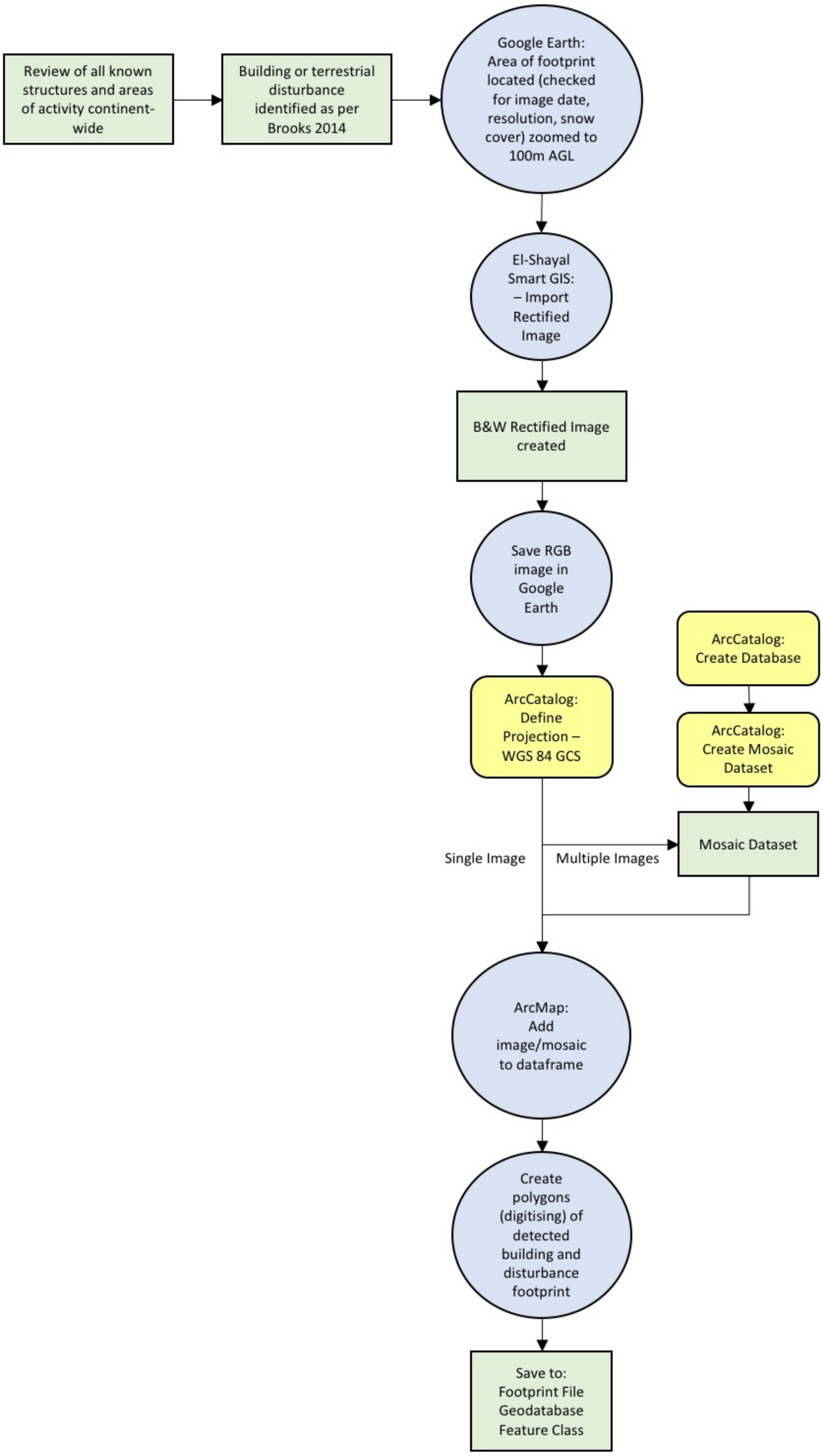
Supplementary Fig. 3. *Footprint mapping example.*

(**a**) Example of initial base layer of mosaicked images, extracted from Google Earth™ for Australia's Davis Station, and (**b**) resultant GIS vector polygons following digitization of buildings (blue) and disturbance (brown) footprint detected in the original images. Credit: Google, 2016, Digital Globe (panel a and b).



Supplementary Fig. 4. *Point locations of additional current and past infrastructure.*

During this study additional areas of infrastructure and activity were identified but were omitted from the measurement data because satellite image resolution was insufficient to enable mapping, the objects were too small to see, or the objects have been removed or buried. The point locations of these are also provided with the dataset (Chapter 4). Blue cells represent locations where data indicates footprint is present, and magenta cells show sites where footprint was previously known to be, with its current status unknown or removed.



Supplementary Fig. 5. *Footprint digitising flowchart.*
This identifies the strategy used to capture footprint data from Google Earth™ through to creation of polygon shapefiles.

Chapter 5

Table S1: *Literature used within the assessment.*

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Chapter 6

Supplementary Information 1: *Antarctic Research Station Systematic Conservation Planning Tool*

Stage 1: Scoping and the planning process

Description: Determination of the geographic boundaries of the planning area is required, along with the techniques to be used to inform the process. The framework and resources (capacity) needed to implement each stage should also be identified.

1. **Geographic boundaries:**
    a. Determining the spatial extent of a station's activities (and cumulative disturbance) where the resulting impacts are at a sufficient level where a cost-benefit would be gained from conservation actions.
        i. Immediate station area;
        ii. wharfs;
        iii. runways; and
        iv. outlying infrastructure.
    b. If station has infrastructure (e.g. ice-free roads) extending to outlying facilities (e.g. landing area or huts), their inclusion should be considered.
    c. If access to outlying facilities is transitory in nature (e.g. over snow), they should be considered for a separate plan. These should include identifying goals and objectives for each location.
        i. Field huts; or
        ii. remote runways.

2. **Techniques:**
    a. Visualisation of data can support planning decisions though spatial analysis (GIS), supported by quantity data.
        i. Values
            1. Presence;
            2. abundance;
            3. diversity;
            4. proximity to station activities; and
            5. external pressures.
        ii. Pressures
            1. Spatial extent (e.g. disturbance footprint);
            2. intensity;
            3. temporal variation; and
            4. trends (i.e. increasing, decreasing, stable).

3. **Values weighting** – weighting may be established from:
    a. A legal and regulatory basis:
        i. National legislation; and
        ii. Madrid Protocol and its annexes (e.g. ASPAs, Specially Protected Species).
    b. Overlapping values
    c. Expert assessment
    d. Assessed importance of values (significance), including:
        i. Concentration;
        ii. distribution;
        iii. richness;

iv. representation;
v. contribution to diversity or ecosystem balance; and
vi. resilience to pressures.

4. **National Antarctic Program's (NAPs) capacity and feasibility for implementation**:
    a. Are proposed actions consistent with domestic and international law and policy (permissible)?
    b. Is there a structure/framework in place to manage conservation implementation?
    c. Is there sufficient financial support to complete implementation?
        i. Implementation and resources required to undertake planning actions will vary in cost, effort, logistical requirements, and intensity. For example, strategies based on alternative planning may require little additional resources compared to actions replacing infrastructure.
        ii. Identification of the resources likely to be required at an early stage will inform the feasibility of objectives, and enable the planning to be shaped with realistic goals.

Stage 2: Identifying and involving stakeholders

Description: Stakeholders are those who operate or use Antarctic research stations. Although stations are generally national government facilities, many are operated by several different agencies, with differing needs and goals. Additionally, many are also operated by, or in concert with, research organisations, foundations, universities, contractors, and military logistical support. The process of identifying stakeholders should include determining the extent they will influence, be affected by, or have responsibility for implementing, the planning process.

As a station's stakeholders will involve the operator, their engagement, and early within the process, is key to successful implementation. Involvement with remaining stakeholders within the process should be proportional to the extent they are affected by the planning.

1. **Identify potential stakeholders for the station**, including any:
    a. Operators (national programs):
        i. Operations/logistics;
        ii. science;
        iii. policy;
        iv. regulators; or
        v. military support.
    b. Users
        i. External research organisations (e.g. Universities, Research Institutes);
        ii. other nation's programs (e.g. shared use or neighbouring stations);
        iii. commercial tourism; or
        iv. recreation by NAP personnel.
    c. COMNAP

2. **Engagement with stakeholders**
    a. At preparation of planning
        i. Contribution to scoping and planning process;
        ii. ascertain individual needs; and
        iii. opportunity for early issue-identification
    b. During planning stages
        i. Presentation of planning concepts;
        ii. identification of issues affecting operations; and
        iii. feedback on likelihood of successful implementation.
    c. Finalisation
        i. Presentation of conservation actions proposed by the planning;
        ii. monitoring, adjusting, and support through implementation; and
        iii. delivery of planning tools for stakeholders (e.g. maps, data layers, education).

Stage 3: Describing the context for Research Stations

Description: Antarctic research stations are inherently varied in history, function, activities, location, and management, providing support for a range of research disciplines. This background requires consideration of the social, economic & political setting for conservation planning. Similarly, the types of threats to natural features that can be mitigated by spatial planning as well as the broad constraints on, and opportunities for, conservation actions, need identification.

1. **Identifying a station's context**
    a. Main role
        i. Logistical hub;
        ii. generalist research support (multidisciplinary research);
        iii. specific research-program support;
        iv. collaborative research support; or
        v. specific purpose (not ongoing).
    b. Operation
        i. Long-term ongoing operation;
        ii. seasonal operation;
        iii. project-specific operation; or
        iv. redundant.
    c. Lifecycle stage and suitability for future needs
        i. Fit for purpose (for foreseeable future);
        ii. requiring further infrastructure (further capabilities needed);
        iii. requiring modernisation (aging infrastructure);
        iv. requiring replacement (approaching end of life);
        v. no longer efficient (passed efficient life span); or
        vi. no longer required (removal or repurposing?).

2. **Awareness and anticipation of pressures**
    a. Causes, extent, severity, and likelihood.
        i. Local pressures, including.:
            1. Disturbance footprint;
            2. building footprint;
            3. contamination;
            4. tourism visitation;
            5. disturbance to wildlife; and
            6. non-native species introduction/transfer.
        ii. External pressures, e.g.:
            1. Changes from climate change (including ozone-related);
            2. marine, atmospheric, or other pollution.

3. **Planning constraints**
    a. Are there health and safety reasons for/against conservation actions? (e.g. some abandoned sites contain hazardous materials).
    b. Is it operationally feasible? (i.e. available resources, logistics, access, and maintenance).
    c. Could actions result in greater environmental pressures? (e.g. release of contaminants)
    d. Is there suitable technological support? (i.e. to prevent adverse outcomes)
    e. Are the planned actions socially acceptable? (i.e. will actions affect acceptable levels of comfort, capabilities, recreation, or well-being for station personnel?)

Stage 4: Identifying conservation goals

Description: Conservation goals for a station will be determined by its context (Stage 3), compliance with the Environmental Principles (Article 3) of the Protocol on Environmental Protection to the Antarctic Treaty), and the legal requirements and cultural expectations of its operator's nation. These should be broad statements which are progressively refined into qualitative goals about the preservation of values. These goals should help identify data requirements (Stage 5).

1. **Determine the broad conservation aims for undertaking planning,** these could include:
    a. Maintenance, improvement, or rehabilitation of surrounding values;
    b. management of a station's footprint;
    c. reduced resource consumption;
    d. reduced load on the environment (e.g. sewage discharge);
    e. reduce risk to the environment (e.g. non-native species, fuel handling);

2. **Set qualitative goals to achieve this aim,** possible examples could include:
    a. Maximising conservation of values in areas of human activities
    b. Streamline conservation into operations
    c. Allow for foreseeable future expansion of facilities
    d. Best practice compliance with the Environmental Principles
    e. Minimise preventable contamination occurring
    f. No establishment of non-native species

Stage 5: Values and pressures (data collection and creation)

Description: Collection and creation of information on biological, scientific, historic, aesthetic, and wilderness values present within the planning area; as well as threatening processes, with a focus on spatially explicit data. Data is collated to map constraints and opportunities for conservation actions. Will also involve predictions about the expansion of threatening processes. This process should identify gaps in information where further assessment, or the precautionary principle, should be applied.

1. **Local pressures**
    a. Spatially-explicit (GIS) data may include:
        1. Disturbance footprint;
        2. roads and paths;
        3. buildings;
        4. infrastructure;
        5. non-native species presence and risk-areas;
        6. intermittent storage; and
        7. areas of recreation (e.g. paths).
    ii. Quantitative data
        1. Sewage, including:
            a. Biological oxygen demand;
            b. suspended solids; and
            c. total volume.
        2. Fuel use
        3. Population
        4. Resource consumption, including:
            a. Area and rock volumes extracted from quarrying or scraping;
            b. potable water extraction.
        5. Environmental incidents
            a. Location;
            b. type;
            c. how they occurred; and
            d. impact.

2. **External pressures**
    a. Climate Change
        i. Observed impacts; and
        ii. predicted future impacts.
    b. Pollution, including:
        i. Marine; and
        ii. atmospheric.

3. **Values**
    a. Nearby ASPAs and value protected
    b. Biological
        i. Plants
            1. Presence;
            2. density;

        3. abundance; and
        4. significance to ecosystem, overall representation, and scientific value.
    ii. Fauna
        1. Presence (including habitat, nesting sites, haul outs);
        2. density;
        3. abundance;
        4. significance to ecosystem, overall representation, and scientific value.
    iii. Unique ecosystems or communities
c. Scientific
    i. Geomorphology
    ii. Fossil sites
d. Historic
    i. HSMs;
    ii. representative of bygone era; or
    iii. relics and artefacts.
e. Intrinsic
    i. Aesthetic
    ii. Wilderness
    iii. Cultural

Stage 6: Reviewing current achievement of objectives

Description: All research station operators will have existing laws, approaches, and management in place to meet their environmental protection obligations under the Antarctic Treaty System. The effectiveness of these, along with any additional domestic measures, should be assessed against field data for their adequacy to achieve desired conservation objectives. This assessment will inform their contribution to, or potential integration within, conservation planning, as well as identify what objectives have already been achieved.

1. **Effectiveness of existing strategies in place,** including:
   a. National strategies
   b. National legislation which ratify the ATS
      i. Permitting;
      ii. environmental impact assessments for new activities;
      iii. prescribed offences; and
      iv. waste management measures.
   c. Effectiveness of biosecurity measures
   d. Assessment of environmental impacts for pre-Protocol activities
   e. Hydrocarbon contamination and remediation action
   f. Sewage treatment
   g. Environmental management systems (including ISO 14001)
   h. Incident reporting
   i. Expeditioner environmental training

2. **Existing conservation aims of NAP,** including:
   a. Effective monitoring programs
   b. Minimisation of fuel spills
   c. Remediation of existing contamination
   d. Waste management
   e. Conservation-supporting science programs

Stage 7: Setting conservation objectives

Description: These should define quantitative objectives for how a NAP wants to meet their conservation goals to address values and pressures data. This will include spatially-explicit targets for the conservation of natural values, ongoing human pressures (e.g. current and future footprint projections), and qualitative objectives related to management strategies for degraded areas, station configurations, and other criteria.

***These will be dependent on a NAPs conservation goals**, but examples could include:*

1. Establishing conservation priority layers based on values assessment for operational use (spatial)
2. No new hydrocarbon contaminated areas (spatial/quantitative)
3. Zero future loss of extant vegetation communities (spatial)
4. Zero/reduced net disturbance footprint growth (spatial)
5. Restoration of disused degraded areas (spatial)
6. Best practice wastewater quality (quantitative)

Stage 8: Applying conservation actions to stations

Description: Applying conservation actions to a station will require a variety of administrative, legal, operational, scientific, and technical pathways. Many components of these actions will already be in place (e.g. environmental impact assessments), but may be more effective if brought together within conservation planning. As the capacity to implement these actions will be finite, priority listing should be provided; based on an assessment of values, risk of further impact, feasibility, and appropriateness.

These may include:

1. **Administrative**
   a. Policy development
      i. Creation of operational policies and codes of conduct that address specific pressures.
   b. Streamlined planning
      i. Provision of readily accessible spatial information on values with weighting of conservation values provided; and
      ii. identification of suitability-tiers for landscape use (based on presence of values, current state, and existing station footprint).
   c. Targeted expeditioner training
      i. For example; disturbance footprint boundaries for plant operators.

2. **Legal**
   a. Integration of explicit conservation planning information with environmental permitting and authorisation processes.
   b. Proposed designation of ASPAs.
   c. Consideration of ASMAs (where multiple Parties are active).

3. **Operational**
   a. Operational planning
      i. Planning future buildings to be centralised and using degraded/lower-value areas;
      ii. provision of planned 'use' areas, including storage, parking, and snow dumping; and
      iii. buffer areas around close-proximity ASMAs.
   b. Land management tools
      i. Barriers around high conservation values;
      ii. elevated walkways;
      iii. identification of opportunities to substitute operations with lower-impact options (e.g. wheeled vehicles versus tracked vehicles); and
      iv. identification and restoration of degraded areas no longer needed for operations.

4. **Scientific**
   a. Conduct monitoring to address gaps in data identified in *Value and pressures* (monitoring should be targeted and specific).

5. **Technical**
   a. Eliminating/substituting problematic fuel infrastructure with reduced-risk technology.
   b. Develop approaches and technologies to enable cost-effective remediation of sites with complex contamination issues.

Stage 9: Maintaining and monitoring achievement of objectives

Description: Management strategies are put in place to ensure conservations actions are effective, sustainable in the long-term, and contribute towards promoting the persistence of values around station activities and meeting objectives. These will require periodic monitoring of values and pressures against baselines or targets to inform planning efficacy. Review periods should also be set to assess progress towards achieving conservation goals.

These could include:

1. **Establishing an implementation plan**.
2. **Establishing a long-term, sustainable, strategy to monitor progress of plan**.
3. **Setting trigger points for review**, such as:
    a. Expansion of footprint area
    b. Detection of decline in biodiversity values
    c. Significant events (e.g. major incident affecting objectives)
    d. Time period (e.g. annual, 5 years)

***Supplementary Information 2**: Case Study Values and Pressures Data Sources: Casey Station*

Values

AAD GIS Layers (from: https://data.aad.gov.au/aadc/portal/drill_down.cfm?gid=1):

- Windmill Island 'Vegetation' dated: 24/5/2006
- 'Penguin colonies'
- 'Seals'
- 'Abandoned penguin colonies'
- 'Lake and ponds'
- 'Lichenometry'
- 'Raised beach sequences'
- 'Exposed rock'

AADC-held Data Records (https://data.aad.gov.au/aadc/portal/drill_down.cfm?id=31):

- AAS4100 – Moss, lichen, and algae cover; rotifers, tardigrades, nematodes, and acari densities in soil.
- AAS3130 – Moss
- AAS4046 – Moss coverage
- AAS4036 – Moss
- AAS4307 – Fauna
- ASAC1219 SP Casey Woehler – Birds
- Windmill Flyingbirds nests points 160 Stark – Flying bird nests.
- Windmill Flyingbirds – Birds
- Adélies 180 Woehler – Birds
- SCAR Biodiversity Database (known to be incomplete)
  (With bounding box of: 110.554676E, 110.495667E, -66.294369S, -66.275664S)

External Data:

- Viewshed: Summerson, R. 2013. *The Protection of Wilderness and Aesthetic Values in Antarctica*. PhD Thesis, University of Melbourne, URL: http://hdl.handle.net/11343/38369
- Important Bird Areas – Shirley Island (ANT146) and Clark Peninsula (ASPA136): Harris, C.M., Lorenz, K., Fishpool, L.D.C., Lascelles, B., Cooper, J., Coria, N.R., Croxall, J.P., Emmerson, L.M., Fijn, R.C., Fraser, W.L., Jouventin, P., Larue, M.A., Le Maho, Y., Lynch, H.J., Naveen, R., Patterson-Fraser, D.L., Peter, H.-U., Poncet, S., Phillips, R.A., Southwell, C.J., Van Franeker, J.A., Weimerskirch, H., Wienecke, B., & Woehler, E.J. 2015. Important Bird Areas in Antarctica 2015. Cambridge: BirdLife International and Environmental Research & Assessment Ltd.

Pressures

AAD Layers (from: https://data.aad.gov.au/aadc/portal/drill_down.cfm?gid=1):

- 'Fixed-wing aircraft approaches'
- 'Helicopter approaches'

- ‘Snow dump map’
- ‘Windmill Island Routes’
- ‘Thala Valley Contaminated Site’
- ‘Spill pathways’
- ‘Quarry Face Surveys’
    - February 2013
    - February 2009
    - March 1999

AADC-held Data Records (https://data.aad.gov.au/aadc/portal/drill_down.cfm?id=31):

- IHIS2684 Fuel Spill sampling
- ASAC_2341 DGGE fingerprinting of bacteria.
- State of the Environment (SOE) Reporting
    - Wastewater
        - Biological Oxygen Demand
            - January 2009-December 2018
        - Suspended solids
            - January 2009-December 2018
    - Population
        - January 2009-May 2016
    - Quarry Operations volume
    - Fuel consumption volumes
        - Generators, vehicles, and incinerators
            - January 2009-December 2015

External Data:

- Fuel spill area: Mcwatters, R.S., Wilkins, D., Spedding, T., Hince, G., Raymond, B., Lagerewskij, G., Terry, D., Wise, L., & Snape, I. 2016. On site remediation of a fuel spill and soil reuse in Antarctica. Science of the Total Environment, 963-973.
- Non-native species: Hughes, K.A., Walsh, S., Convey, P., Richards, S., & Bergstrom, D.M. 2005. Alien fly populations established at two Antarctic research stations. *Polar Biology,* 28(7), 568-570.
- Incidents associated with: Brooks, S.T., Jabour, J., Sharman, A.J., & Bergstrom, D.M. 2018. An analysis of environmental incidents for a national Antarctic program. Journal of Environmental Management, 212, 340-348.

Original layers created for this project:

- 2018 Casey Heavy Disturbance – produced from Worldview-3 imagery, captured 27/1/2018.
- 2018 Casey Medium Disturbance – produced from Worldview-3 imagery, captured 27/1/2018.
- 2015 Casey Heavy Disturbance – produced from AAS 5024 UAV-imagery.
- 2015 Casey Medium Disturbance – produced from AAS 5024 UAV-imagery.
- 2008 Casey Heavy Disturbance – produced from data associated with: Brooks, S.T. 2014. Developing a Standardised Approach to Measuring the Environmental Footprint of Antarctic Research Stations. Journal of Environmental Assessment Policy and Management, 16(04), 1450037.
- 2008 Casey Medium Disturbance – produced from aerial imagery and field data opportunistically collected in association with: Brooks, S.T. 2014. Developing a Standardised

Approach to Measuring the Environmental Footprint of Antarctic Research Stations. Journal of Environmental Assessment Policy and Management, 16(04), 1450037.

- 2002 Casey Heavy Disturbance – produced from 2002 AADC-held Orthophoto
- 2002 Casey Medium Disturbance – produced from 2002 AADC-held Orthophoto
- Combined Heavy Disturbance – combination of 2002, 2008, 2015, and 2018 layers.
- Combined Medium Disturbance – combination of 2002, 2008, 2015, and 2018 layers.